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Volume 1. Technical Results

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This report documents results of 42 hazardous waste combustion tests performed on 11 full-scale industrial boilers. The report discusses the boiler operating conditions, measured organic and other gaseous emissions, and the achieved destruction efficiency of principal organic hazardous constituents (POHC's) present in the waste. The report is divided in two volumes. Volume I presents a summary of all test data, discusses conclusions, and highlights trends in POHC destruction and other byproduct emissions with respect to boiler operation and POHC type. Volume II is a compendium of boiler specific test data summarized to provide readers with sufficient details to perform their own analyses. Major volatile POHC's investigated were carbon tetrachloride, chlorobenzene, trichloroethylene, and toluene. The destruction efficiency of 14 other volatile and semivolatile hazardous organics is also reported. In general, industrial boilers tested achieved greater than 99.99 percent POHC destruction efficiency under conditions investigated. Although not clearly evident, the collected data point out lower destruction efficiencies with transient or off-specification burner and feedrate conditions. Emissions of identifiable products of incomplete combustion (PIC's) were generally one to two orders of magnitude greater than POHC breakthrough emissions. Lower PIC emissions accompanied greater POHC destruction efficiencies.

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VOLUME I.
TECHNICAL RESULTS

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

In 1981 the Office of Solid Waste, under RCRA, developed regulations for the incineration of hazardous waste. Industrial boilers are exempt from these regulations. In response to environmental concerns regarding this practice, the Agency has undertaken a multidisciplinary research program to determine the operating practices and destruction efficiency of boilers burning hazardous wastes as information necessary to regulation development and the Regulatory Impact Analysis (RIA) required under Executive Order 12291. One important area of this research program is the field testing of full-scale industrial boilers burning hazardous waste for disposal and energy recovery. Associated research activities include fundamental and pilot-scale waste destruction studies and the evaluation of sampling and analytical methods for particular wastes. This report documents the results of the field test program to characterize destruction efficiencies of representative industrial boilers burning hazardous wastes under typical industrial operating practices. The report is in two volumes. Volume I provides the technical results for the entire field test program. Volume II contains the data obtained at each of the field tests.

Requests for further information regarding combustion of hazardous wastes in high temperature industrial processes should be directed to the Energy Pollution Control Division, IERL, Cincinnati.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

This report documents results of 42 hazardous waste combustion tests performed on 11 full-scale industrial boilers. The report discusses the boiler operating conditions, measured organic and other gaseous emissions, and the achieved destruction efficiency of principal organic hazardous constituents (POHC's) present in the waste. The report is divided in two volumes. Volume I presents a summary of all test data, dicusses conclusions, and highlights trends in POHC destruction and other byproduct emissions with respect to boiler operation and POHC type. Volume II is a compendium of boiler-specific test data summarized to provide readers with sufficient details to perform their own analyses. Major volatile POHC's investigated were carbon tetrachloride, chlorobenzene, trichloroethylene, and toluene. The destruction efficiency of 14 other volatile and semivolatile hazardous organics is also reported. In general, industrial boilers tested achieved greater than 99.99 percent POHC destruction efficiency under conditions investigated. Although not clearly evident, the collected data point out lower destruction efficiencies with transient or off-specification burner and feedrate conditions. These conditions were at times manifested by increases in combustible emissions or burner flame instability. Lower limits of measured destruction efficiencies were generally found to increase with furnace waterwall heat release rate (kW/m^2) and measured NO$_x$ emission, possibly indicating dependence of POHC destruction on the furnace thermal environment. Emissions of identifiable products of incomplete combustion (PIC's) were generally one to two orders of magnitude greater than POHC breakthrough emissions. Lower PIC emissions accompanied greater POHC destruction efficiencies. These and other trends are highlighted to point out areas requiring further research.

This report was submitted in partial fulfillment of Contract No. 68-02-3188 by Acurex Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from 1981 to 1984, and work was completed as of June 1984.

CONTENTS

Foreword iii
Abstract iv
Figure viii
Table ix
Acknowledgement xiii

1.1 Background 1
1.2 Field Test Program Objective 2
1.3 Approach 2

2 Test Site Description, Operation, and Waste Fuels 3

2.1 Site A 5

- 2.1.1 Fuel Feed 7
- 2.1.2 Boiler Operation 7
- 2.1.3 Fuel Composition 9

2.2 Site B 9

- 2.2.1 Fuel Feed 12
- 2.2.2 Boiler Operation 12
- 2.2.3 Fuel Composition 12

2.3 Site C 15

- 2.3.1 Fuel Feed 15
- 2.3.2 Boiler Operation 15
- 2.3.3 Fuel Composition 15

2.4 Site D 19

- 2.4.1 Fuel Feed 19
- 2.4.2 Boiler Operation 20
- 2.4.3 Fuel Composition 22

2.5 Site E 22

- 2.5.1 Fuel Feed 25
- 2.5.2 Boiler Operation 26
- 2.5.3 Fuel Composition 28

CONTENTS (Continued)

2.6 Site F 30

2.6.1 Fuel Feed 32
2.6.2 Boiler Operation 32
2.6.3 Fuel Composition 32

2.7 Site G 35

2.7.1 THROX Feed 37
2.7.2 THROX Operation 37
2.7.3 Feed Composition 38

2.8 Site H 40

2.8.1 Fuel Feed 41
2.8.2 Boiler Operation 42
2.8.3 Fuel Composition 42

2.9 Site I 42

2.9.1 Fuel Feed 45
2.9.2 Boiler Operation 46
2.9.3 Fuel Composition 48

2.10 Site J 48

2.10.1 Fuel Feed 49
2.10.2 Boiler Operation 50
2.10.3 Fuel Composition 50

2.11 Site K 53

2.11.1 Fuel Feed 53
2.11.2 Boiler Operation 54
2.11.3 Fuel Composition 54

2.12 Summary of Boiler Design, Fuels, and Operation . . 54

3 Sampling and Analysis Protocols 63
4 Emissions Results 70

4.1 Criteria Emissions 70

4.1.1 Gaseous Emissions 72
4.1.2 C_1 to C_6 Hydrocarbons 79
4.1.3 Particulate and HCl Emissions 81

CONTENTS (Concluded)

4.2 POHC Emissions 81

4.2.1 Baseline Emissions 84
4.2.2 Cofire Emissions 87
4.2.3 Summary of Major POHC Emissions 94

4.3 Other Organic Emissions 97

4.3.1 Flue Gas Volatile Organics. 101
4.3.2 Other Discharge Streams Organics 108

5 POHC Destruction Efficiency 111

5.1 Summary of Results 111

5.1.1 Site E Results 111
5.1.2 Site F Results 118
5.1.3 Site H Results 118
5.1.4 Site I Results 121
5.1.5 Site J Results 121
5.1.6 Other DRE Results 124

5.2 Summary of Results and Interpretation of Trends . . 127

5.2.1 Combustion Efficiency 127
5.2.2 POHC Concentration in the Waste 131
5.2.3 NO_x Emissions 131
5.2.4 Surface Heat Release Rate 133

6 Conclusions 139

6.1 Effects of Combustion Efficiency on DRE 139
6.2 Effect of Waste Fuel POHC Concentration on DRE . . . 140
6.3 Effect of NO_x and Surface Heat Release on DRE . . . 140
6.4 PIC Emissions 141
6.5 Solid and Liquid Waste Streams 141

References 142
Appendix A -- Data Listing 143

FIGURES

Number		Page
1	Sampling protocol schematic -- site H	64
2	VOST schematic (reference 8)	66
3	Modified EPA Method 5 schematic	67
4	Relationship of volatile chlorinated PIC's versus POHC's sites D, E, F, and G	106
5	PIC emissions versus test average POHC DRE	109
6	Site E DRE versus combustion efficiency	119
7	Site E DRE versus NO_x	120
8	Site J DRE versus combustion efficiency	122
9	Site J DRE versus NO_x	123
10	Effect of combustion efficiency on test average POHC DRE	129
11	Effect of combustion efficiency on chlorinated POHC DRE	130
12	Effect of POHC concentration on DRE	132
13	DRE trends with NO_x emissions -- test averaged DRE's	134
14	DRE trends of chlorinated POHC's with NO_x emissions	135
15	DRE trends with NO_x emissions -- site average DRE's	136
16	Effect of surface heat release rate on DRE -- test average data	137
17	Effect of surface heat release rate on DRE -- site average data	138

TABLES

Number		Page
1	Waste-Boiler Candidate Test Matrix	4
2	Waste-Boiler Test Matrix	6
3	Boiler Operating Conditions -- Site A	8
4	Fuel Analysis -- Site A	10
5	Creosote Analysis Results -- Site A	11
6	Boiler Operating Conditions -- Site B	13
7	Waste Sample Composition -- Site B	14
8	Boiler Operating Conditions -- Site C	16
9	Composition of Phenolic Waste -- Site C	17
10	Organic Compounds Detected in the Phenolic Waste -- Site C	18
11	Boiler Operating Conditions -- Site D	21
12	Fuel Composition -- Site D	23
13	Boiler Design and Operating Conditions -- Site E	24
14	Boiler Operating Conditions -- Site E	27
15	Fuel Composition -- Site E	29
16	Waste Fuel Analysis Results -- Site E	31
17	Approximate Composition of Purge Thinner -- Site F	33
18	Boiler Operating Conditions -- Site F	34
19	Fuel Analysis -- Site F	36
20	Volatile Organic Composition of Thinner -- Site F	37

TABLES (Continued)

Number		Page
21	Typical THROX Feed Composition -- Site F	38
22	Summary of THROX Operating Conditions -- Site G	39
23	Feed Ultimate Analysis -- Site G	40
24	THROX Feed Analysis Results -- Site G	41
25	Boiler Operating Conditions -- Site H	43
26	Ultimate Fuel Analysis -- Site H	44
27	Waste Fuel POHC Concentration -- Site H	44
28	Composition of the Spiked Aniline Waste -- Site I	46
29	Boiler Operating Conditions -- Site I	47
30	POHC Composition of Waste Feed -- Site I	49
31	Boiler Operating Conditions -- Site J	51
32	Fuel Ultimate Analysis -- Site J	52
33	POHC's Composition of Test Fuel -- Site J	52
34	Boiler Operating Conditions -- Site K	55
35	Ultimate Analysis of Fuel -- Site K	56
36	Feed Analysis -- Site K	57
37	Boiler Summary	58
38	Summary of Boiler Operation and Fuel Parameters	62
39	Sampling and Analysis Protocols	69
40	Summary of Tests	71
41	Criteria Flue Gas Emissions	73
42	C_1 to C_6 Hydrocarbon Emissions Summary	80
43	Particulate and HCl Gas Emissions	82
44	Waste Feed Concentration of Major Organic Compounds . .	83

TABLES (Continued)

Number Page

45 Waste Fuel POHC Concentration Normalized by Waste Fuel Heat Contribution 85

46 Baseline Organic Emissions (Primary Fuel Only) 86

47 Carbon Tetrachloride (CCl_4) Emission Results 89

48 Trichloroethylene (TCE) Emission Results 90

49 Chlorobenzene ($Cl\phi$) Emission Results 91

50 Toluene Emission Results 92

51 Summary of Major Volatile POHC Emissions 95

52 Emission Trends of Methylmethacrylate at Site E 96

53 Emission Results of Semivolatile Organics 98

54 Volatile Organics Sought in GC/MS Analysis 99

55 Semivolatile Organics Sought in the GC/MS Analysis and Their Detection Limits 100

56 Summary of Selected Volatile PIC's -- Site D 102

57 Summary of Selected Volatile PIC's -- Site E 103

58 Summary of Selected Volatile PIC's -- Site F 104

59 Summary of Selected Volatile PIC's -- Site G 104

60 Relationship of Volatile Chlorinated PIC's versus POHC's -- Sites D, E, F, and G 107

61 Mass Flowrates of Organics in Makeup Water and Recovery Scrubber Discharge Streams, µg/s -- Site G 110

62 Mass Flowrates of Organics in Makeup Water and HCl Scrubber Discharge Streams, µg/s -- Site G 110

63 Volatile Organics DRE's -- Site E 112

64 Volatile Organics -- Site F 113

65 Volatile Organics -- Site H 114

TABLES (Concluded)

Number		Page
66	Volatile Organics -- Site I	115
67	Volatile Organics -- Site J	116
68	Volatile Organics -- DRE Results	125
69	Semivolatile Organic DRE's	126
70	Summary of Test Average DRE's for Volatile POHC's	128

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SECTION 1

INTRODUCTION

This report presents emission results obtained from field measurements and laboratory analyses of samples from 11 industrial boiler sites burning hazardous wastes. The purpose of these tests was to determine the thermal destruction efficiency of industrial boilers burning hazardous organic chemicals for a broad range of boiler design and fuel type categories operating under typical industrial conditions.

1.1 BACKGROUND

Thermal destruction of hazardous wastes by direct incineration or by cofiring in boilers, furnaces, or kilns can be more economically and environmentally advantageous than landfills or chemical treatment. Direct incineration of hazardous wastes is regulated by Part 264 of the Resource Conservation and Recovery Act (RCRA) which was adopted in January 1981. These regulations limit atmospheric emissions. Specifically, principal organic hazardous constituents (POHC's) in the waste must exhibit a destruction and removal efficiency (DRE) of $\geq$ 99.99 percent defined as:

$$\mathrm{DRE} = (M_{feed} - M_{stack})/M_{feed} \times 100$$

where:

M_{feed} = Mass flowrate of a POHC in the waste fuel

M_{stack} = Stack emission rate of a POHC

POHC's are the compounds, listed in Appendix VIII of the May 1980 RCRA amendments, that were found in significant concentrations in the waste. This specification of DRE gives credit for POHC removal in ash streams. For chlorinated wastes, the RCRA standards also require 99 percent removal of HCl. However, these standards do not apply to the use of hazardous chemical wastes as fuels for heat recovery furnaces such as power boilers and process heaters. Also excluded from these regulations are high-temperature industrial process refractory furnaces such as cement kilns and steel furnaces.

The use of organic chemical waste as a supplement to fossil fuels for industrial boilers is a widespread practice. Since many hazardous wastes have significant heating value, the practice of cofiring in industrial boilers is often an attractive alternative to incineration, chemical treatment, or landfill disposal while meeting the RCRA goal of maximum recovery of natural resources. Recent estimates indicate that 264 million metric tons of hazardous waste are generated annually (Reference 1). The organic chemical industry as a whole generates a significant portion of this waste and operates an estimated 5,500 industrial boilers in the size category of greater than 2.9 MW (10 million Btu/hr) (Reference 2).

At the time of the 1981 RCRA standards for hazardous waste incinerators, technical data on the DRE of hazardous organic compounds in the thermal environment of industrial boilers was essentially unavailable. This lack of data precluded the EPA from evaluating the need and the nature of regulatory standards controlling this practice. Therefore, through the Office of Solid Waste (OSW) and the Office of Research and Development (ORD), EPA initiated a program to evaluate the technical and overall environmental acceptability of the use of hazardous waste as fuels for industrial boilers. The program included thermal destruction research using laboratory- and pilot-scale simulators as well as field testing of full-scale industrial boilers. This report summarizes the results of the full-scale boiler test program.

1.2 FIELD TEST PROGRAM OBJECTIVE

The primary objective of the field test program was to determine the DRE of industrial boilers burning hazardous organic chemicals in wastes under current industry operating practice. Following initial tests, field measurements and analytical activities were extended to determine the overall environmental burden of hazardous waste firing. Organic emission analyses included quantitation of organic compounds other than POHC's for identifiable products of incomplete combustion (PIC's). In addition, selected changes in boiler operating conditions were implemented to identify the potential impact of operating conditions on DRE and PIC emissions. Ultimately, the goal of the test program was to provide guidelines on boiler design, fuels, and operating conditions which are likely to achieve the desired DRE for a given hazardous waste.

1.3 APPROACH

Candidate test sites were screened based on representativeness of the boiler design and wastes being fired, and the availability and accessibility for cofiring tests. Within this context, preference was given to sites and waste fuels which were viewed as being less likely to attain a high level of waste destruction. A test matrix developed by EPA was used to rank boiler/waste combinations less likely to achieve a high POHC DRE and to aid in site selection (Reference 2). To facilitate intrasource comparison, the majority of test boilers were cofired with an artificially spiked waste fuel. Spiked organics typically were carbon tetrachloride, chlorobenzene, and trichloroethylene which ranked high on the list of difficult compounds to destroy.

The results presented in this report represent the complete data base available on hazardous waste destruction in full-scale industrial boilers. Ongoing R&D and field tests are aimed at identifying DRE trends with transient boiler operation and other nonsteady boiler conditions.

SECTION 2

TEST SITE DESCRIPTION, OPERATION, AND WASTE FUELS

Test sites were selected to evaluate waste destruction feasibility over a broad range of boiler designs and waste characteristics. Estimates of the industrial boiler population indicate that the chemical industry operates about 5,500 boilers with individual heat input capacity of greater than 2.9 MW (10^7 Btu/hr). These boilers are accessible to a significant percentage of U.S. hazardous waste generation which is estimated at 264 million metric tons annually (Reference 1). These boilers are diverse in design, fuels burned, and operating conditions. Also, hazardous organic wastes vary widely in physical and chemical properties and in the types and amounts of hazardous compounds they contain. Based on several studies of the industrial boiler population and waste fuels, a test matrix was developed to aid the selection of candidate test sites for field testing of DRE and organic emissions.

Table 1 illustrates the test matrix and highlights the most desirable boiler type/waste type categories for testing in this program. Waste fuels are characterized by POHC groups and physical qualifiers. POHC groups are based on the heat of combustion of individual compounds as follows:

POHC Group	Range in Heat of Combustion kcal/g	10^3 Btu/lb
I	0-3.99	0-7.19
II	4.00-6.99	7.20-12.59
III	7.00-10.00+	12.61-18.0+

This distinction was made on the assumption that POHC's with a low heat of combustion would be relatively more difficult to destroy than POHC's with high heat of combustion. Scientific evidence, however, has shown that heat of combustion is not a good measure of POHC destructibility (Reference 3). Physical characteristics of the waste were segregated according to the amount of water and the inorganic solid contents. Therefore, the higher the water and inorganic solid content, the lower the destructibility of the waste. Water in the waste also plays a role of combustion temperature cooling in the cofired flame, therefore the peak temperatures are reduced and POHC destruction may also be reduced. Of course the degree by which water with waste will decrease the combustion temperature also depends on the amount of waste to primary fuel ratio utilized.

TABLE 1. WASTE-BOILER CANDIDATE TEST MATRIX[a]

← Worst case

Waste descriptors		Boiler descriptors				
		Boiler type:	Firetube	Watertube	Watertube	Watertube
		Fuel type:	Oil, gas	Oil, gas	Oil, gas	Coal
POHC group	Physical qualifiers	Capacity (million Btu/hr):	10 to 50	10 to 100	100+	100+
I	Aqueous		X	X		
	Metals					
	Solids		NA	NA	NA	X
	Nonaqueous		X	X	X	
II				X		
III	Aqueous			X		
	Metals					
	Solids		NA	NA	NA	X
	Nonaqueous		X	X	X	

↑ Worst case

[a] Reference 2.

NA = not applicable.

X = indicates most desirable boiler/waste combination for testing.

From a boiler design viewpoint, the test matrix addressed the major design categories of firetubes and watertubes and typical fossil fuels burned in these units. An earlier study on the estimates of time-temperature profile in boilers had shown that although most boilers provide sufficiently high furnace temperature and residence time for efficient destruction of organic compounds, smaller units such as firetubes and small watertubes provide the least safety factor of time at high temperature (Reference 4).

Table 2 lists the eleven test sites selected for the field test program in the framework of the developed test matrix. Test sites are designated by the letters A through K. The majority of the selected boilers were watertubes, in the 2.9 to 29 MW (10^7 to 10^8 Btu/hr) size category, burning either natural gas or heavy oil as the primary fuel. The waste fuel was generally nonaqueous (low or no water content). All three POHC group categories were represented with heat of combustion for individual organic compounds in the range of 0.24 kcal/g (carbon tetrachloride) to 10.1 kcal/g (toluene). Waste fuels available at the selected test sites were cofired as found (normal operating practices) or artificially spiked with POHC I and II categories compounds to broaden the range of POHC destruction data and facilitate intrasource comparison. Most test programs were based on a baseline test (primary fossil fuel only) followed by a minimum of three cofired tests for replication of results.

This section discusses each of the eleven test sites with detailed descriptions of boiler types, operation, waste fuels, and other relevant engineering data including waste pretreatment, feed mechanism, and emission control and discharge streams. Steady-state boiler operation was sought during all testing to minimize the variation in test parameters with potential impact on DRE's and other organic emissions. However, changes in operating conditions, fuel composition, and flowrate did occur and these instances are discussed. Volume II of this report (Data Supplement) provides schematics of individual boilers and fuel feed systems.

2.1 SITE A

The industrial boiler tested at site A was a wood-fired Keeler CP watertube steam generator. The boiler has a rated capacity of 1.3 kg/s (10,000 lb/hr) of saturated steam at 1.71 MPa (250 psig). The furnace has a heat exchange area of 286 m^2 (3,080 ft^2) of which 106 m^2 (1,144 ft^2) is waterwall area and a volume of approximately 17.4 m^3 (613 ft^3). The lower furnace is refractory lined with cast iron grates, a flyash reinjection opening, and overfire air nozzles cast into the rear refractory bridgewall. On the front wall, the furnace was equipped with two cleanout doors for the grates and two cleanout doors for under the grates. The boiler was also equipped with a fuel oil air-atomized burner capable of 1.3 kg/s (10,000 lb/hr) of steam. This burner was not in operation during the tests. The primary fuel for this boiler was a mixture of wood chips, bark, and sawdust. Creosote waste sludge from the wood treating facility was mixed with the wood providing an estimated 40 percent of the total heat input.

TABLE 2. WASTE-BOILER TEST MATRIX

← Worst case

↑ Worst case

Waste descriptors		Boiler descriptors				
		Boiler type:	Firetube	Watertube	Watertube	Watertube
		Fuel type:	Oil, gas	Oil, gas	Oil, gas	Coal
POHC group	Physical qualifiers	Capacity (million Btu/hr):	10 to 50	10 to 100	100+	100+
I	Aqueous					
	Metals					
	Solids		NA	NA	NA	
	Nonaqueous		G, J[a]	D, F, I, K	E	H
II			G, J	D, F, I, K	E	H
III	Aqueous		B	A		
	Metals					
	Solids		NA	NA	NA	
	Nonaqueous		G, J	I, K	C	

[a] Letters indicate test site designation.

NA = not applicable.

2.1.1 Fuel Feed

Creosote sludge was fed from an uncovered tank onto a belt conveyor carrying the wood waste to the boiler furnace. The wood waste was fed into the furnace through two injectors equipped with variable speed auger units. Combustion occurred primarily on the stationary grate with some suspension burning as the wood and creosote were injected into the furnace. The boiler was equipped with ambient underfire, overfire, and reinjection air, each fed with a separate fan. Bottom ash was removed through the two furnace access doors. Flyash collected in the boiler outlet hopper was reinjected into the furnace. The boiler flue gas duct was also equipped with a Western Precipitation multiclone size 9VM-36-6 for particulate collection. Flyash trapped by the multiclone was collected by gravity in a drum located directly below the hopper. An induced draft (ID) fan provided balanced draft for the boiler.

2.1.2 Boiler Operation

Four cofiring tests were made. The first test was an attempted baseline run, with wood waste only. However, analyses of the fuels showed that the baseline wood fuel was most likely contaminated with creosote sludge. Therefore, the attempted baseline test was considered a cofire test. Table 3 summarizes the range in boiler operation, fuels, and ash stream flowrates during these three tests.

Prior to the start of the tests the wood waste and creosote sludge waste were premixed. To accomplish this mixing, the creosote sludge waste was dripped onto the wood waste as it was transported to the boiler fuel hopper. From the hopper the mixture was transported to the fuel storage area where it was stored in preparation for testing. During the mixing, measurements performed to determine the creosote sludge flowrate indicated a rate of approximately 50 ml/s (430 lb/hr) corresponding to 0.21 to 0.25 creosote sludge to wood waste weight ratio.

Sufficient instrumentation to permit detailed measurements of boiler operating parameters was not available at this site. This lack of instrumentation is particularly critical for the measurements of wood and creosote sludge input rates into the furnace and ash discharge rates since these impact POHC's flowrate and DRE calculations. However, there was evidence of transient boiler operation during the tests.

Large fluctuations in O_2, CO_2, and CO measured in the flue gas were indicative of this transient operation of the site A boiler. These transient conditions were in part attributed to fluctuating steam demands on the boiler and to the nature of the fuel and its feed mechanism. Although not recorded, steam loads were probably changing significantly during the test program. Wood-fired boilers generally operate under large fluctuations in O_2, CO_2, and CO. This is due to the poor air-fuel mixing of bed combustion and to the heterogenous physical and chemical properties of wood waste which can vary in size distribution, moisture and heat contents.

TABLE 3. BOILER OPERATING CONDITIONS -- SITE A

Boiler parameters	Cofired tests (wood waste plus creosote sludge)
Wood waste feedrate,[a] kg/s (lb/hr)	0.25 to 0.23 (2,020 to 1,750)
Creosote sludge feedrate, g/s (lb/hr)	54 (430)
Creosote/wood waste, percent heat input	40/60
Total heat input, MW (million Btu/hr)	5.0 to 5.7 (17.2 to 18.7)
Surface heat release rate, kW/m^2 (10^3 $Btu/hr\text{-}ft^2$)	290 to 330 (110 to 125)
Boiler efficiency, percent	63
Bottom ash discharge rate[c], g/s (lb/hr)	0.44 (3.5)
Flyash discharge rate[c], g/s (lb/lhr)	1.0 (8)
Flue gas discharge rate,[b] dscm/m (dscf/m)	157 to 168 (5,560 to 5,960)

[a] Dry basis.
[b] Calculated from stack gas flowrate measurements.
[c] Estimates based on hopper collection measurements.

2.1.3 Fuel Composition

Table 4 lists the ultimate analysis results of fuels burned during each of the tests. The fuel composition reported on a dry basis showed that, except for moisture content, the composition of the fuel mixture during tests 2, 3, and 4 is little different than that of test 1. This reflects the creosote contamination of the wood during the attempted baseline test. Moisture, measured by heating the fuel to 100°C (212°F) was found to be about 36 percent higher for tests 2, 3, and 4 than that of test 1. The steam used in the wood treating process would account for moisture in the creosote. The increase in moisture content of the mixed fuel burned during tests 2, 3, and 4 can be interpreted as a higher creosote content in the fuel mixture for these tests.

The fuel compositions of the tests were used to estimate the fuel feedrates based on stack gas measurements. The results indicate that fuel feedrate (wood plus creosote) ranged between 0.28 kg/s (2,200 lb/hr) and 0.30 kg/s (2,400 lb/hr) on a dry basis with creosote accounting for 54 g/s (430 lb/hr) or about 40 percent of the total heat input. Boiler efficiency was about 63 percent for both the baseline and the cofired tests using the ASME heat loss method of calculation. This suggests boiler operation at a maximum continuous rating of 1.5 kg/s (12,000 lb/hr) of steam throughout the test program.

GC/MS analyses of creosote waste samples collected during the test program were performed to quantify specific polycyclic organic materials (POM) and other semivolatile and nonvolatile organic compounds. The results of the GC/MS analyses are summarized in Table 5. Major components, those whose concentration exceeded about 5 mg/ml (5,000 ppm), are pentachlorophenol, naphthalene, fluorene, phenanthrene, pyrene, and biphenyl. Among these, only pentachlorophenol, fluorene, and naphthalene are compounds listed as hazardous in the Resource Conservation and Recovery Act (RCRA) Appendix VIII. Other detected compounds considered hazardous by Appendix VIII are phenol, 2,4-dimethylphenol, 4-nitrophenol fluoranthene and chrysene whose concentrations varied from 0.06 to 2.4 mg/ml (60 to 2,400 ppm).

The composition and concentration of compounds in the creosote waste showed little variation among samples. Sample 1 creosote waste sample showed generally higher concentrations for each of the compounds detected. However, for most cases the difference between these concentrations and those of the other two tests fall within the sensitivity of analytical instrumentation and procedures used. Overall, the combined concentration of these compounds accounts for approximately 4 to 8 percent of the waste. The remaining 92 to 96 percent are considered to be high molecular weight aliphatic and aromatic compounds of heavy tar residue.

2.2 SITE B

The industrial boiler tested at site B was a Cleaver-Brooks (CB) 2.4-MW (250-hp) firetube with a rated steam flowrate of approximately 1.06 kg/sec

TABLE 4. FUEL ANALYSIS[a] -- SITE A

Composition, percent by weight		Test 1 cofire[b]	Test 2 cofire	Test 3 cofire	Test 4 cofire	Test average	Creosote
Carbon		50.54	52.21	51.12	50.93	51.20	88.45
Hydrogen		5.58	5.85	6.18	5.94	5.89	8.74
Nitrogen		0.10	0.10	0.12	0.10	0.11	2.03
Chlorine		0.24	0.15	0.21	0.21	.21	0.51
Ash		0.70	0.65	0.82	1.11	0.82	0.26
Oxygen (by difference)		42.84	41.04	41.55	41.71	41.79	0
H_2O[c]		31.78	43.29	43.69	42.74	40.38	24.14[d]
Higher heating value[e]	kJ/kg	19,740	20,320	19,590	19,790	19,860	38,730
	(Btu/lb)	(8,503)	(8,757)	(8,440)	(8,525)	(8,518)	16,690

[a] Dry basis.

[b] Wood waste burned during the first test contained some solvent contaminants noticeable by volatile hydrocarbons emanating from fuel at ambient temperature.

[c] A portion of the moisture concentration is attributable to volatile hydrocarbons with boiling points less than 100°C (212°F).

[d] Estimated values, H_2O by difference assuming O_2 concentration to be negligible.

[e] Heating values may be underestimated because of probable loss of volatile hydrocarbons during analysis.

TABLE 5. CREOSOTE ANALYSIS RESULTS -- SITE A

Composition, mg/ml	Sample 1	Sample 2	Sample 3
Acids:			
Phenol[a]	1.3	0.80	0.58
2,4-Dimethylphenol[a]	1.3	0.36	0.30
4-Nitrophenol[a]	0.28	0.20	0.18
Pentachlorophenol[a]	6.0	2.2	2.2
Base/neutrals:			
Bis(2-chloroethoxy)-methane	0.48	ND	ND
2,4-Dinitrotoluene	0.78	ND	ND
2,6-Dinitrotoluene	1.3	ND	ND
Naphthalene[a]	19	6.0	5.4
Acenaphthylene	ND	0.14	0.12
Acenaphthene	0.24	0.16	0.14
Fluorene[a]	7.6	5.0	4.4
Phenanthrene	13	7.0	6.4
Anthracene	0.26	3.0	2.4
Fluoranthene[a]	0.14	0.06	0.06
Pyrene	15	8.4	6.2
Chrysene[a]	ND	ND	2.4
Dyphenylamine	0.18	0.12	ND
Other compounds:			
Methylnaphthalenes	2.2	1.4	1.3
Biphenyl	8.6	8.4	5.2
Dibenzofuran	0.86	0.88	0.96
Cyclopenta(d,e,f)phenanthrene	0.68	0.62	0.58
Methylpyrenes	1.9	1.6	0.78

[a] Principal organic hazardous constituents per RCRA Appendix VIII present in significant concentrations.

ND = not detected. Concentrations are below the detection limit of 1 μg/ml.

(8,400 lb/hr) of saturated steam at 1.08 MPa (150 psig). The furnace has a waterwall area of approximately 8 m^2 (83 ft^2) and a volume of 1.1 m^3 (39 ft^3). The flue gas makes four passes, once through the firebox and three times through the convective tube before it exits the stack.

2.2.1 Fuel Feed

Natural gas is introduced through a single ring burner. Waste fuel consisted of an alkyd resin wastewater produced from paint manufacturing operations. When cofiring the alkyd resin, the waste was introduced through the air-atomized oil burner centered in the gas ring.

2.2.2 Boiler Operation

Four tests were performed: one baseline and three cofiring tests. During the baseline test, flue gas emissions and boiler inputs were measured with the boiler burning only natural gas. Table 6 summarizes the boiler operation, fuel, and waste flowrates during all tests. The waste heat input for test 2 cannot be determined accurately since the waste fuel heating value is unreliable. During cofiring, several nonsteady-state conditions and operational upsets were recorded. These were primarily caused by waste feed problems due to insufficient mixing of the alkyd resin wastewater. This feed problem resulted in fluctuations of waste flow and several waste flow cutoffs due to pluggage of strainers.

During the baseline test, the boiler was running at 73 percent efficiency (heat loss method). This dropped to 62 percent for the cofiring tests, primarily due to the quantity of wastewater to be evaporated.

2.2.3 Fuel Composition

GC/MS and GC/FID analyses of wastewater samples collected during the three cofiring tests were performed to quantify the type and quantity of POHC's and other priority organic compounds. Table 7 lists the analysis of the wastes burned during the cofiring tests. As shown, the water content varied dramatically among the waste samples from 28 to 99.9 percent. This is indicative of the generally poor mixing of the alkyd wastewater. The analyses presented for the second and third tests are from composites of three grab samples taken over the course of each test. The three analyses presented for the fourth test are from different grab samples. They indicate the large variation in waste stream composition over the course of the test.

Analytical results from test 4 samples are considered most representative of the organic concentration of the wastewater. Based on a water inlet and outlet calculation, the most reliable data for wastewater flowrate and organic content is 0.11 m^3/hr (0.48 gpm) containing 10 to 15 percent organic material of which toluene accounts for approximately 0.01 to 10 percent.

TABLE 6. BOILER OPERATING CONDITIONS -- SITE B

Boiler parameters	Test 1 baseline	Test 2 cofire	Test 3 cofire	Test 4 cofire
Natural gas feedrate, m^3/min (dscfh)	1.30 (2,770)	1.30 (2,770)	1.24 (2,630)	1.12 (2,380)
Steam pressure, kPa (psig)	630 (92)	510 (75)	540 (78)	570 (82)
Wastewater feedrate, m^3/hr (gpm)	0 0	0.13 (0.59)	0.12 (0.54)	0.12 (0.53)
Heat input, MW[a] (million Btu/hr)	0.86 (2.9)	>0.85 (>2.9)	0.81 (2.8)	0.73 (2.5)
Waste heat input, percent of total	0	~0.1	0.14	0.5
Volumetric heat release rate, kW/m^3 (Btu/hr-ft^3)	770 (74,000)	770 (74,000)	745 (72,000)	665 (64,000)
Moisture in flue gas, percent	15.4	18.7	15.2	19.6
O_2, percent dry	4.9	5.3	5.7	5.0
Flue gas temperature, °C (°F)	164 328	160 320	159 319	158 316

TABLE 7. WASTE SAMPLE COMPOSITION -- SITE B

Compound, mg/l	Test 2	Test 3	Test 4[a]		
Water (by difference)	279	999	999	995	996
RCRA Appendix VIII					
Naphthalene	6.8	0.36	0.071	1.7	0.1
Pentachlorophenol	1.6	ND	0.016	0.288	0.048
Toluene	129,000	0.100	8.2	550	0.3
Other semivolatile and nonvolatile					
Xylenes	469,000	8.2	268	2,760	2,280
C_3-alkylbenzenes	22,600	400	27	405	2
C_4-alkylbenzenes	2	3.7	0.100	46	1
Benzoic acid	1,180	695	310	1,190	1,120
Benzaldehyde	ND	ND	0.075	ND	ND
1,2 benzenedicarboxylic acid	>270[b]	3.5	0.27	0.32	ND
Methyl-1,1-biphenyl	0.68	0.26	0.039	0.7	ND
Methylnaphthalenes	ND	0.019	ND	0.17	ND
Higher heating value, kJ/l	25,340	34.0	29.1	181	121
(Btu/gal)	(90,900)	(122)	(104)	(650)	(433)

[a] Three samples were taken and analyzed separately.

[b] Detector saturated.

[c] Large differences in fuel properties are due to poor mixing. Test 4 samples are considered most representative of typical wastewater burned in the boiler.

ND = not detected.

2.3 SITE C

The industrial boiler tested at site C was a Babcock & Wilcox (B&W) wall-fired steam generator. The boiler nameplate capacity is 29 kg/s (230,000 lb/hr) of superheated steam at 1.71 MPa (250 psig) and 269°C (516°F). However, typical steam loads are limited to 18.9 kg/s (150,000 lb/hr). The furnace has a volume of 322 m^3 (11,400 ft^2) and a waterwall area of 170 m^2 (1,800 ft^2). Six burners, arranged in two rows of three burners each, are capable of burning gas and oil. Generally, the oil guns are used for waste fuel injection while the gas ring supplies either natural gas or process waste gas. The unit is not equipped with an air pollution control device.

2.3.1 Fuel Feed

The waste fuel burned in the boiler contained primarily α-methyl styrene dimers and phenolic and benzene residues, including phenol, methylenebisphenol, and cumene. Typically, the firing rate of the phenolic waste fuel provides about 40 to 50 percent of the total heat input to the boiler based on a higher heating value ranging from 38 to 39 MJ/liter (135,000 to 140,000 Btu/gal). The waste fuel is injected into the boiler furnace through the available oil guns at ambient temperature and is steam atomized.

2.3.2 Boiler Operation

Four tests were performed: one baseline and three cofired tests. During the baseline test run, flue gas was sampled with the boiler burning only natural gas with three burners in operation. Triplicate cofired tests were subsequently performed with a mixture of natural gas and phenolic waste. During these cofired tests four burners were in operation, one for the phenolic waste and three for natural gas. Combustion air was fed through all six available burners. Table 8 summarizes the boiler operation and fuel feedrates during these tests.

Boiler steam load averaged 7.76 kg/s (61,500 lb/hr) during the baseline test. Average steam loads for the cofired tests ranged from 6.97 kg/s (55,300 lb/hr) to 7.95 kg/s (63,000 lb/hr). These loads correspond to 24 to 27 percent of the boiler nameplate capacity of 29 kg/s (230,000 lb/hr). Heat input from the phenolic waste ranged from 37 to 39 percent of the total heat input based on an average phenolic waste heating value of 37.6 MJ/liter (135,000 Btu/gal). Excess oxygen was about 10 percent for each test. No boiler upset conditions or transients were recorded during any of the tests. Boiler efficiency calculated from the ASME heat loss method was about 81 percent for all four tests.

2.3.3 Fuel Composition

The GC/MS and GC/FID analyses of waste samples collected during the three cofiring tests were performed to quantify specific polycyclic organic materials (POM) and other organic compounds. Ultimate analysis results are presented in Table 9 and the organic composition results in Table 10.

TABLE 8. BOILER OPERATING CONDITIONS -- SITE C

Boiler parameters	Test 1 baseline	Test 2 cofire	Test 3 cofire	Test 4 cofire
Steam flow, kg/s	7.76	7.95	7.29	6.97
(1,000 lb/hr)	(61.5)	(63.0)	(57.8)	(55.3)
Natural gas flow, l/s	661	434	417	393
(1,000 scfh)	(84.0)	(55.2)	(53.0)	(49.9)
Waste fuel flow, ml/s	0	270	250	253
(gph)		(256)	(238)	(241)
Total heat input,[a] MW	25.1	25.9	25.3	24.5
(million Btu/hr)	(85.7)	(88.3)	(86.2)	(83.4)
Waste heat input[a], percent of total	0	38	37	39
Volumetric heat kW/m^3	78	80	78	76
release rate, $(Btu/hr\text{-}ft^3)$	(7,500)	(7,700)	(7,500)	(7,300)
Gas pressure at burner, Pa	523	458	421	548
(psig)	(2.10)	(1.84)	(1.69)	(2.20)
Moisture in flue gas, percent	12.2	11.0	9.8	10.8
O_2, percent dry	10	9.7	10.5	10.7
Furnace pressure, Pa	-95	-95	-87	-90
(in. H_2O)	(0.38)	(-0.38)	(-0.35)	(-0.36)
Stack opacity, percent	10	16	15	15

[a] Based on 3.76 MJ/liter (135,000 Btu/gal) for the phenolic waste and 38.0 MJ/m^3 (1,020 Btu/ft^3) for natural gas.

TABLE 9. COMPOSITION OF PHENOLIC WASTE[a] -- SITE C

Composition, percent by weight	Test 2 cofire	Test 3 cofire	Test 4 cofire
Carbon	83.23	84.02	82.99
Hydrogen	7.84	7.91	7.81
Nitrogen	0.69	0.65	0.80
Sulfur	0.07	0.06	0.07
Chlorine	0.02	0.03	0.01
Ash	0.08	0.08	0.07
Oxygen (by difference)	8.07	7.25	8.20
Moisture, percent	0.45	0.50	0.60
Higher heating value, kJ/kg	38,372	38,435	39,072
(Btu/lb)	16,498	16,525	16,799

[a] Dry basis.

TABLE 10. ORGANIC COMPOUNDS DETECTED IN THE PHENOLIC WASTE[a] -- SITE C

Compound, g/l	Test 1 baseline	Test 2 cofire	Test 3 cofire
RCRA Appendix VIII			
Phenol	56	47	53
Bis(2-ethylhexyl)phthalate	0.055	0.042	0.031
Dibutylphthalate	ND	ND	0.120
Other Semivolatiles and Nonvolatiles[a]			
C_3-alkylbenzene[b]	100	110	100
C_3-alkylbenzene[b]	38	40	45
Benzene acetaldehyde	4.7	6.4	5.0
2,2'-methylenebisphenol	3.3	1.8	0.46
4,4'-methylenebisphenol	3.4	2.2	0.37
Pyrene	0.010	0.004	0.004
$C_{15}H_{16}O$	7.4	8.1	7.5
$C_{15}H_{16}O$	1.6	2.2	3.0
$C_{18}H_{20}$	24	29	38
$C_{16}H_{18}O$	33	46	38
Total organics, percent	27	29	29

[a] With the exception of pyrene and C_3-alkylbenzenes, the identification of these compounds is tentative, concentrations are approximate.

[b] Different isomers.

ND = not detected, below 1.0 μg/ml

For the duration of these tests, the waste composition remained essentially unchanged with phenol and C_3-alkylbenzenes constituting the major organic compounds detected in the analysis. Other major aromatics detected were unidentified C_{15}, C_{16}, and C_{18} compounds.

2.4 SITE D

The industrial boiler tested at site D was a balanced draft B&W field-erected watertube boiler with a rated steam flowrate of 11.4 kg/s (90,000 lb/hr) of saturated steam at 1.80 MPa (260 psig). The unit, installed in 1946 as a coal-burning stoker, is currently equipped with four conventional single-register oil- and gas-fired B&W burners arranged in a two-by-two matrix. The total furnace surface area is 613 m^2 (6,600 ft^2) of which 23 percent is waterwall area. The remaining 77 percent is refractory surface including the furnace floor. The furnace volume is 62 m^3 (2,200 ft^3). This arrangement provides a waterwall surface heat release rate of about 220 kW/m^2 (71,000 $Btu/hr\text{-}ft^2$) and a volumetric heat release rate of 400 kW/m^3 (39,000 $Btu/hr\text{-}ft^3$) at maximum heat input rate. Combustion air is preheated to approximately 127°C (260°F) by means of a tubular air preheater.

The boiler has essentially no particulate control device since a multiclone, which was part of the original unit configuration for particulate collection during coal burning, was removed during the conversion to oil and gas burning. However, the remaining flue cavities provide some low-efficiency flyash collection capability. Existing furnace outlet hoppers, also part of the original coal-burning design, provide some additional particulate collection. During gas and oil burning, however, this particulate consists primarily of refractory material abrated from furnace surfaces.

2.4.1 Fuel Feed

Incineration efficiency of two solvent waste streams was investigated in the test program. These two streams, labeled no. 3 and no. 6, were selected from several available at the site primarily because they contained hazardous chlorinated compounds.

Typically, solvent streams no. 3 and 6 have the following approximate composition:

Solvent stream no. 3	Solvent stream no. 6
Xylene, 15 percent	Toluene, 90 to 92 percent
Methanol, 70 percent	Dichloroethyl ether, 6 to 7 percent
Tetrachloroethylene, 5 percent	Water, 1 to 4 percent
Diphenylether, 2 percent	
Water, 8 percent	

Tetrachloroethylene (PCE), and dichloroethyl ether (BCEE) are POHC's listed in RCRA Appendix VIII.

During the test program, each waste solvent was fed to one of the lower burners. The waste solvent was pumped from the bottom of a rail car and metered through a venturi with a flowmeter integrator. The lower level burner was used to inject the waste solvents into the boiler at ambient temperature with steam atomization. A recirculation line from one of the pumps to the top of the rail car was installed for this test program with the intent of minimizing stratification of the waste solvents in the rail car. However, during cofiring with solvent stream no. 3, the recirculation system was only partially successful in maintaining a relatively constant concentration of organic compounds to the boiler.

2.4.2 Boiler Operation

Seven separate tests were performed: one baseline and six cofired. During the baseline test, flue gas was sampled with the boiler burning only no. 6 oil through all four available burners. Three of the six cofired tests were subsequently performed with a combination of no. 6 oil and waste solvent no. 3. Three of the burners were firing oil and one burner was firing waste solvent. The remaining three cofired tests were performed with a combination of oil and waste solvent no. 6. During these final tests only three burners were in operation, the top two on oil and one lower burner on waste solvent. Both combustion air and fuel to burner no. 4 were shut off during these three tests.

Table 11 summarizes the boiler operation and the fuel flowrates during each of these tests. Tests 1 through 4 were performed with steam load at about 9.0 kg/s (70,000 lb/hr) corresponding to about 180 kW/m^2 (57,000 $Btu/hr\text{-}ft^2$) waterwall surface heat release rate. Tests 5 through 7 were performed with a steam load of about 5.7 kg/s (45,000 lb/hr) corresponding to about 0.10 MW/m^2 (33,000 $Btu/hr\text{-}ft^2$) waterwall surface heat release rate. Bulk gas residence time in the furnace was estimated to be approximately 1.1 sec for the high load tests (1, 2, 3, and 4) and 1.3 sec for the low load tests (5, 6, and 7). The heat input attributed to solvent stream no. 3 varied from 18 to 30 percent because of the change in composition primarily during test 4. For tests 5, 6, and 7 solvent stream no. 6 accounted for nearly half the heat input to the boiler.

During the entire test program the boiler was operated on manual override to minimize fluctuations in steam load and fuel flow throughout each test. However, some operational upsets were recorded for some tests. During test 2, in particular, flame-outs for the waste solvent burner occurred. They occurred primarily because of waste solvent feed problems and improper flame scanner settings experienced at the start of the cofired tests. Also during test 2, filter screens at the pumping station had to be frequently cleaned to avoid sudden loss or oscillations in the waste flow. Nevertheless, waste solvent flow fluctuations were experienced throughout the test program, especially with solvent no. 3 whose composition was found to be highly variable. Smoke emissions were often the result of burner flame-outs as well as sudden changes in waste solvent flow. Although in most instances testing was discontinued during smoke episodes, some flue gas sampling did take place during periods of high smoke (control room smoke alarm was set for

TABLE 11. BOILER OPERATING CONDITIONS -- SITE D

Boiling parameters	Baseline	Solvent stream no. 3 tetrachloroethylene (PCE)			Solvent stream no. 6 bis(2-chloroethyl) ether (BCEE)		
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Steam flow, kg/s	8.8	9.0	8.6	9.0	5.8	5.7	5.6
(thousand lb/hr)	(70)	(71)	(68)	(71)	(46)	(45)	(44)
No. 6 oil flow, ml/s	630	491	471	530	196	192	186
(gpm)	(10.0)	(7.79)	(7.47)	(8.40)	(3.10)	(3.05)	(2.94)
Waste solvent flow, ml/s	0	264	274	257	187	187	192
(gpm)		(4.19)	(4.35)	(4.08)	(2.97)	(2.97)	(3.04)
Total heat input, MW	25	28	27	26	15	14	14
(million Btu/hr)	(86)	(95)	(91)	(88)	(51)	(49)	(49)
Waste solvent heat input, percent of total	0	30	29	18	48	46	48
Volumetric heat release rate, kW/m^3	400	445	420	410	240	230	230
($Btu/hr\text{-}ft^3$)	(39,000)	(43,000)	(41,000)	(40,000)	(23,000)	(22,000)	(22,000)
Number of burners firing	4	4	4	4	3	3	3
Furnace draft, kPa	-0.04	-0.04	-0.04	-0.04	-0.03	-0.03	-0.03
(in H_2O)	(-0.15)	(-0.16)	(-0.15)	(-0.15)	(-0.15)	(-0.15)	(-0.15)
Moisture in the flue gas, percent	9.89	9.45	8.86	11.1	8.46	8.06	8.11
O_2 out of boiler, percent	3.7	3.5	4.2	4.0	3.8	4.4	5.0
Number of smoke episodes	0	3	1	0	0	3	0

Ringelman >1.0) especially during test 2 and occasionally during tests 3 and 6.

2.4.3 Fuel Composition

For each of the seven tests, no. 6 fuel oil samples and waste solvent samples were taken for subsequent analysis. Table 12 summarizes the composition of these fuels by ultimate analysis and the concentration of POHC's for each of the tests. Significant losses in the analyses for carbon, hydrogen, and nitrogen were the result of large concentrations of methanol in solvent stream no. 3. The significant drop in the chloride concentration, from 22 percent in tests 2 and 3 to 3.9 percent in test 4, is indicative of the stratification of PCE in the tank car. These chloride data on solvent stream no. 3 suggest that the concentration of methanol increased sharply during test 4. This caused a significant reduction in the heating value of the waste solvent from 29,300 to 20,600 kJ/kg (about 12,600 to 8,920 Btu/lb). In contrast, the ultimate analysis of solvent stream no. 6 suggests that this fuel composition remained relatively constant. Its heating value ranged from about 38,800 to 43,100 kJ/kg (16,700 to 18,000 Btu/lb); nearly that of no. 6 fuel oil due to the large concentration of toluene.

Waste solvent samples, collected during each cofiring test, were analyzed specifically by the GC/Hall technique for PCE and BCEE in solvent streams no. 3 and 6, respectively. Since both PCE and BCEE are listed in RCRA Appendix VIII, determining the DRE of these compounds was the primary objective of this test program. Table 12 summarizes the concentration of these compounds in mg/ml for their respective waste solvents. PCE concentration ranged from 285 mg/ml for test 2 to 70 mg/ml for test 4. Test 3 PCE concentration ranged from 70 mg/ml to 295 mg/ml averaging about 170 mg/ml. These laboratory results for solvent stream no. 3 show the severe stratification of PCE in the tank car. This stratification occurred despite attempts to circulate the solvent in the tank car.

2.5 SITE E

The industrial boiler tested at site E was a forced draft CE Type 30-A-12 packaged watertube boiler with a maximum capacity of 13.9 kg/s (110,000 lb/hr) of superheated steam at 2.94 MPa (425 psig) and 315°C (600°F). The unit, installed in 1971, is equipped with one 0.91m (36 in.) dual-air-register COEN burner. No. 6 fuel oil is injected through a COEN 3.5 MV gun. Natural gas is injected in the furnace through a gas ring. The burner was modified to permit injection of waste fuels. This positive pressure furnace has a volume of 41.9 m^3 (1,480 ft^3) and a heating surface of 665 m^2 (7,158 ft^2). This arrangement provides volumetric and surface heat release rates of 960 kW/m^3 (92,500 $Btu/hr\text{-}ft^3$) and 60.3 kW/m^2 (19,100 $Btu/hr\text{-}ft^2$), respectively, at maximum heat input capacity. The boiler is not equipped with a particulate control device. Combustion air is not preheated. Detailed engineering design and operating data were available for this boiler. Table 13 summarizes these data provided by the manufacturer for four typical steam load levels with no. 6 oil as the primary fuel.

TABLE 12. FUEL COMPOSITION -- SITE D

	No. 6 oil	Solvent stream no. 3			Solvent stream no. 6		
Composition, percent by weight	Tests 1 through 7	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Carbon	87.94	25.7[a]	31.1[a]	27.8[a]	82.50	81.49	85.18
Hydrogen	11.30	1.8[a]	9.0[a]	7.5[a]	9.10	9.02	9.57
Nitrogen	0.29	0.51[a]	0.7[a]	0.7[a]	0.48	0.72	0.43
Sulfur	0.30	0.02	0.02	0.09	0.01	0.01	0.01
Chlorine	0.03	22.0	22.0	3.9	1.57	2.45	2.19
Oxygen[b] (by difference)	0	NA	NA	NA	6.13	6.11	2.53
Ash	0.05	0.11	0.17	0.10	0.02	<0.01	<0.01
Moisture	0.18	0.68	7.80	11.25	0.20	0.20	0.09
Higher heating value, kJ/kg	43,114	29,410	29,192	20,621	41,812	38,770	39,686
Higher heating value, (Btu/lb)	18,537	12,645	12,551	8,866	17,977	16,669	17,063
	POHC concentration in waste solvent, mg/ml						
PCE	0	295	163	69.6	0	0	0
BCEE	0	0	0	0	41.0	40.2	40.2

[a] Significant losses observed in carbon, hydrogen, and nitrogen.

NA = no accurate oxygen was possible.

TABLE 13. BOILER DESIGN AND OPERATING CONDITIONS -- SITE E

Steam load, kg/s	13.9	10.4	6.94	3.47
(lb/hr)	(110,000)	(82,500)	(55,000)	(27,500)
Total heat input,[a] MW	40.1	30.3	20.1	9.9
(million Btu/hr)	(137)	(104)	(68.6)	(33.9)
Volumetric heat release kW/m^3	958	724	480	237
rate, (Btu/hr-ft^3)	(92,500)	(70,300)	(46,400)	(22,800)
No. 6 oil firing rate, kg/s	0.933	0.706	0.468	0.231
(lb/hr)	(7,400)	(5,600)	(3,710)	(1,830)
Surface heat kW/m^2	60.3	45.7	30.3	14.8
release rate, (Btu/hr-ft^2)	(19,100)	(14,500)	(9,600)	(4,700)
Combustion excess air, percent	15	15	15	15
Boiler thermal efficiency, percent	88.1	88.3	88.5	88.1
Gas throughput, kg/s	15.8	11.9	7.88	3.87
(lb/hr)	(125,500)	(94,000)	(62,500)	(30,700)
Flame front temperature, °C	1,980	1980	1,980	1,980
(°F)	(3,600)	(3,600)	(3,600)	(3,600)
Average furnace temperature, °C	1,590	1,565	1,530	1,480
(°F)	(2,900)	(2,850)	(2,790)	(2,700)
Minimum furnace outlet °C	1,200	1,150	1,080	980
temperature, (°F)	(2,200)	(2,100)	(1,980)	(1,800)
Economizer gas inlet °C	363	323	290	263
temperature, (°F)	(685)	(615)	(555)	(505)
Economizer gas outlet °C	166	146	135	124
temperature, (°F)	(330)	(295)	(275)	(255)
Furnace gas residence time, sec	0.38	0.48	0.65	1.0

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[a] Based on no. 6 oil high heating value of 43,000 kJ/kg (18,500 Btu/lb).

2.5.1 Fuel Feed

Incineration efficiency of three organic waste streams was investigated in the test program when cofired with either no. 6 fuel oil or natural gas. Two of these waste streams were generated by the site processes, the other was prepared by artificially spiking one of these streams with hazardous chlorinated organics. The composition of these three waste streams can be summarized as follows:

Waste Stream No. 1	Waste Stream No. 2	Waste Stream No. 3
Methyl methacrylate, 1%	Methyl methacrylate, 1%	Toluene, 80%
α-Hydroxy methyl isobutyrate, 11%	α-Hydroxy methyl isobutyrate, 10%	Methyl methacrylate, 20%
α-Hydroxy isobutyrate methyl ether, 7%	α-Hydroxy isobutyrate methyl ether, 6%	
Fluxing oils, 81%	Carbon tetrachloride, 2% Chlorobenzene (Clϕ), 2% Trichloroethylene, 2% Fluxing oils, 77%	

Waste stream no. 1 was a green-black residual oil byproduct commonly referred to as third-stage bottoms (TSB) from the distillation of crude methyl methacrylate (MMA). Waste stream no. 2 was manufactured at the site by spiking waste stream no. 1 with carbon tetrachloride (CCl_4), chlorobenzene (Clϕ), and trichloroethylene (TCE), each accounting for approximately 2 percent of the waste by volume. Although waste stream no. 3 was a minor waste byproduct of the test site, it was included in the test program to provide a maximum concentration of MMA in the waste to the boiler. MMA, CCl_4, Clϕ, and TCE are POHC's listed in RCRA Appendix VIII.

No. 6 fuel oil was injected through a large Y-jet steam-atomized oil gun located in the burner center. A spare oil gun is inserted and used only during the time required for cleaning the main gun. This generally takes a few minutes and occurred rarely during the test periods. Waste fuel mixtures were prepared in a trailer tanker containing TSB waste. Each of the waste streams then passed through a 10,600-liter (2,800-gal) mixing tank prior to being filtered and fed to the boiler. Waste fuels were injected using two separate steam-atomized COEN 1 MV guns each located on either side of the center oil gun. Although waste fuel feed lines to each gun were equipped with a metering valve, there was no indication of the waste flowrate through each gun. This occasionally resulted in an imbalance of waste fuel between the two guns resulting in smoke emissions. Waste fuel was injected at ambient temperature.

The orientation of the spray nozzles together with the waste flow imbalance between the guns was found to affect smoke formation. Optimum orientation of waste gun nozzles seemed to correspond to pointing away from the oil spray from the center gun. Apparently, any interference of fuel jets caused fuel-rich "pockets" which resulted in soot formation and smoke emissions.

2.5.2 Boiler Operation

Nine separate tests were performed: one baseline and eight cofire. Table 14 summarizes the boiler operation and the fuel flowrates during each of these tests. During the baseline test no. 1, flue gas was sampled with the boiler burning only no. 6 oil. During test no. 2, heat input from no. 6 oil was supplemented with the waste fuel available at the site, that is, TSB containing MMA as the POHC of interest. During tests 3 through 7 the TSB waste fuel spiked with chlorinated POHC's was used to supplement the no. 6 fuel oil. Fuels burned during test no. 8 consisted of chlorinated TSB and natural gas to investigate the effect of primary fuel type on destruction of this artificial waste fuel. In the last test, no. 9, a mixture of toluene and MMA was burned with natural gas. The firing rate of MMA during test no. 9 was significantly higher than that of any other cofiring tests.

During these tests, emission rates under three different heat input rates were investigated. Tests 1 through 5 and test 8 were performed with boiler steam load at about 7.0 kg/s (55,000 lb/hr) corresponding to about 32.0 MW/m^2 (10,300 $Btu/hr\text{-}ft^2$) surface heat release rate or 50 percent of capacity. Gas residence time at this firing rate is approximately 0.65 sec at an estimated bulk furnace temperature of 1,530°C (2,790°F). Test no. 7 was performed at a boiler steam load of about 10.2 kg/s (80,000 lb/hr) corresponding to the upper limit of typical operation for this unit. Surface heat release rate at this load was approximately 47.2 MW/m^2 (15,000 $Btu/hr\text{-}ft^2$) with a gas residence time of about 0.5 sec and an estimated bulk furnace temperature of about 1,590°C (2,900°F). Tests 6 and 9 were performed at the low boiler load conditions of about 5.3 kg/s (42,000 lb/hr). At this heat input rate, the corresponding surface heat release rate was about 23.5 MW/m^2 (7,500 $Btu/hr\text{-}ft^2$) with a gas residence time of 1.0 sec for test 6 and 1.1 sec for test 7. The estimated bulk temperature for tests 6 and 7 was 1,480°C (2,700°F). This boiler load corresponds to the lower limit for waste incineration specified by the site.

During the entire test program the boiler was operated on manual override to maintain constant boiler loads and fuel feedrates. However, operational upsets occurred during some tests. These led primarily to smoke emissions and required frequent boiler operator attention and adjustments. These operational upsets can best be summarized as follows:

- During the switch from a single primary fuel to a cofiring condition with chlorinated TSB (test 3), several periods of smoke emissions were recorded. These emissions, which occurred during a time period preceding the actual testing, were caused by waste flow control problems.

TABLE 14. BOILER OPERATING CONDITIONS -- SITE E

	No. 6 oil (baseline)	No. 6 oil and TSB	No. 6 oil and chlorinated TSB					Natural gas and chlorinated TSB	Natural gas and toluene MMA mix
Boiler parameters	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Steam flow, kg/s (10^3 lb/hr)	6.8 (54)	7.0 (56)	7.0 (56)	7.0 (56)	6.9 (55)	5.1 (41)	10.2 (81)	7.2 (57)	5.5 (44)
No. 6 oil flow, ml/s (gpm)	515 (8.18)	448 (7.12)	352 (5.59)	375 (5.95)	358 (5.68)	214 (3.40)	616 (9.79)	0	0
Natural gas flow, l/s (10^3 cfm)	0	0	0	0	0	0	0	354 (45.0)	204 (26.0)
Waste fuel flow, ml/s (gpm)	0	195 (3.10)	236 (3.75)	260 (4.13)	250 (3.97)	261 (4.15)	249 (3.96)	259 (4.11)	235 (3.74)
Total heat input, MW (million Btu/hr)	21.2 (72.3)	23.6 (80.5)	20.2 (68.9)	21.5 (73.5)	20.5 (70.0)	15.4 (52.4)	31.4 (107)	20.5 (70.1)	17.2 (58.6)
Heat from no. 6 oil, percent	100	78	72	72	72	57	81	0	0
Furnace pressure, kPa (in H_2O)	0.37 (1.5)	0.42 (1.7)	0.47 (1.9)	0.69 (2.8)	0.59 (2.4)	0.18 (0.73)	1.6 (6.5)	0.60 (2.5)	0.24 (0.98)
Heat from natural gas, percent	0	0	0	0	0	0	0	67	44
Waste fuel heat input, percent of total	0	22	28	28	28	43	19	33	56
Boiler out O_2, percent dry	3.0	3.9	4.4	6.0	5.9	4.9	6.0	4.6	5.3
Boiler thermal efficiency percent	88.4	80.4	89.1	88.0	89.4	94.1	85.5	96.9	88.9
Number of smoke emission episodes[a]	0	1	8	4	3	0	3[b]	0[c]	0[c]

[a] Number of recorded smoke alarms. Ringelman number ≥ 0.6 during smoke alarm.

[b] Based on CO emission response. Plant smoke meter was inoperable during this high load test 7.

[c] Visible plume but no smoke alarm took place during these tests.

- Smoke emissions during flue gas sampling occurred for each of the cofired tests. These smoke emissions, which were most prevalent during test 3, were caused primarily by a surge in waste fuel flow.

- Sensitivity of smoke emissions to waste gun orientation and flow surges was evident. Generally higher excess air levels were adopted during tests 4 through 9 to minimize smoke formation in the absence of more accurate waste flow control.

Smoke episodes that occurred during each test were recorded. This information, which can be relevant in the interpretation of the emission and destruction of POHC's in the waste fuel, is discussed further in sections 5 and 6.

Fuel flows for no. 6 fuel oil and waste fuels were available from several meters at this site. Heat input data for these fuels were based on flows calculated from totalizer meters which recorded the total gallons consumed during each test. The heat input from the waste fuel during tests 2 through 5 and test 8, when boiler steam load was about 7.0 kg/s (55,000 lb/hr) ranged from 20 to 33 percent of the total heat input. The contribution of waste fuel to the total heat input during tests 6 and 9, when boiler steam load was about 5.3 kg/s (40,000 lb/hr), increased to about 40 to 50 percent. During the highest steam load investigated, test 7, heat input from the chlorinated waste was about 20 percent.

Boiler efficiencies, calculated based on heat input and output data, were above 90 percent during tests 6 and 8. These efficiency results may indicate an underestimation of the fuel oil flowrate as measured by the totalizer meter for test 6 and of the natural gas for test 8 or by an overestimation of the steam output. In light of typical boiler performance in the 85 to 90 percent range, efficiencies calculated for tests 6 and 8 are considered suspect.

2.5.3 Fuel Composition

For each of the nine tests, no. 6 fuel oil and waste fuel samples were taken for subsequent analysis. Table 15 summarizes the composition of these fuels by ultimate analysis for each of the tests. The no. 6 fuel oil sample corresponds to a composite of oil samples collected during tests 1 through 7. Chloride concentration in the fuel oil was about 0.4 percent noticeably higher than that of TSB waste fuel and the mixture of toluene and MMA. The spiking of TSB with chlorinated POHC's (carbon tetrachloride, chlorobenzene, and trichloroethylene) increased the chloride concentration of the waste fuel to about 1.5 to 3.4 percent. The nitrogen content of each of the waste streams was higher than that of the fuel oil. In contrast, each waste fuel was essentially devoid of sulfur and inorganic ash in comparison with the fuel oil. The TSB waste contained water in quantities ranging from about 1.3 to 4 percent. The toluene and MMA mixture cofired during test 9 with natural gas and no. 6 fuel oil contained insignificant amounts of water. Chlorination of the TSB waste fuel caused a drop in the heating value from 27,300 kJ/kg (11,740 Btu/lb) to the range of 24,500 to 26,700 kJ/kg

TABLE 15. FUEL COMPOSITION -- SITE E

Composition, percent by weight	No. 6 oil	TSB	TSB + Cl Mix (CCl_4, ClΦ, TCE)						Toluene/ MMA
	Test 1 through 7	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Carbon	6.64	59.90	57.67	56.06	54.11	55.45	55.99	57.21	77.02
Hydrogen	2.06	8.56	8.53	8.00	8.02	8.27	7.91	8.54	9.02
Nitrogen	0.34	2.06	2.50	2.70	2.21	2.47	3.00	2.05	1.05
Sulfur	0.55	0.01	0.01	0.01	0.08	0.02	0.03	0.01	0.03
Chlorine	0.40	0.10	1.80	2.06	1.53	3.00	3.35	2.36	0.16
Oxygen (by difference)	0	27.63	25.46	28.46	31.45	28.29	27.29	28.48	12.52
Ash	0.05	0.01	0.05	0.03	0.03	0.02	0.02	0.02	<0.01
Moisture	0.2	1.73	3.98	2.71	2.57	2.50	2.41	1.33	0.20
Higher heating value/ kJ/kg (Btu/lb)	43,393 (18,657)	27,308 (11,741)	25,526 (10,975)	25,836 (11,108)	24,528 (10,546)	26,154 (11,245)	25,761 (11,076)	26,726 (11,491)	37,076 (15,941)

(10,550 to 11,490 Btu/lb). The heating value of the toluene and MMA mixture was significantly higher than the TSB waste fuel because of its large concentration of toluene.

Waste fuel samples were collected during each cofiring test for subsequent laboratory analyses of POHC concentrations. GC/Hall analytical technique was used to measure the concentration of chlorinated organics, CCl_4, $Cl\phi$, and TCE, which were used to spike the TSB waste fuel available at the site. The GC/FID technique was used to analyze for MMA, α-hydroxy-methylisobutyrate (MOB), and α-hydroxy-methylisobutyrate methylether (MEMOB) commonly present in the TSB waste fuel and the toluene and MMA mixture. Since CCl_4, $Cl\phi$, TCE, and MMA are listed in RCRA Appendix VIII, measurements of these emissions and quantification of their DRE's was the primary objective of this test program. DRE's for MOB and MEMOB were also determined through analyses of waste fuel concentrations and emission rates.

Table 16 summarizes the concentration of these organic compounds in mg/ml for their respective waste fuels incincerated during each of the nine tests. The TSB waste fuel cofired during test 2 was void of any chlorinated organic as anticipated. The concentrations of MMA, MOB, and MEMOB were about 34, 360, and 72 mg/ml, respectively. The concentrations of these compounds varied little in each of the chlorinated waste fuel samples of tests 3 through 8. MMA varied only from about 33 to 50 mg/ml, MOB ranged from 280 to 450 mg/ml and MEMOB from 50 to 90 mg/ml. Chlorinated organics added to the TSB waste fuels of tests 3 through 8 resulted in CCl_4 concentrations of 27 to 33 mg/ml, $Cl\phi$ concentrations in the range of 15 to 19 mg/ml, and TCE concentrations of 24 to 31 mg/ml. During test 9 the toluene and MMA mixture was not artificially chlorinated. However, minute concentrations of CCl_4 and TCE were detected in the waste sample. This may have been the result of the waste fuel feed line being contaminated with chlorinated TSB from previous tests. The MMA concentration in this waste fuel was increased to about 120 mg/ml, while both MOB and MEMOB concentrations decreased to about 21 and 6.7 mg/ml, respectively. The concentration of toluene for this fuel was then calculated at about 85 percent or 850 mg/ml.

2.6 SITE F

The industrial boiler tested at site F was a balanced draft Babcock & Wilcox (B&W) Integral Furnace F-18/48 watertube boiler with a rated steam capacity of 7.6 kg/s (60,000 lb/hr) of saturated steam at 1.4 MPa (200 psig). The furnace volume is approximately 96 m^3 (3,400 ft^3) with an estimated heating surface of about 100 m^2 (1,100 ft^2). At rated steam capacity the estimated gas residence time in the furnace is 2 sec with volumetric and surface heat release rates of 217 kW/m^3 (20,600 $Btu/hr\text{-}ft^3$) and 198 kW/m^2 (63,600 $Btu/hr\text{-}ft^2$), respectively, and a bulk gas temperature of 1,370°C (2,500°F). This boiler, originally capable of coal burning, is equipped with two B&W circular burners for burning no. 6 oil, no. 2 oil, natural gas, or propane arranged in two levels. Residual oil is steam atomized. The waste solvent is introduced through a separate pressure-atomized Y-jet B&W oil gun near the center of the lower burner.

TABLE 16. WASTE FUEL ANALYSIS RESULTS[a] -- SITE E

	Waste Fuel Description							
	TSB	Chlorinated TSB						Toluene/MMA mixture
Compound mg/ml	Test 2 cofire	Test 3 cofire	Test 4 cofire	Test 5 cofire	Test 6 cofire	Test 7 cofire	Test 8 cofire	Test 9 cofire
CCl_4[b]	ND	27.7	28.7	29.1	29.1	33.4	26.9	0.09
$Cl\phi$[b]	ND	16.5	15.9	16.1	17.9	19.1	14.5	ND
TCE[b]	ND	28.7	29.4	28.9	28.1	31.0	23.9	0.09
MMA[b]	34.1	37.5	33.0	49.7	46.2	47.3	37.4	119
MOB	357	446	377	332	290	294	343	20.5
MEMOB	71.8	84.2	70.8	64.1	52.0	57.6	84.4	6.7

[a] All samples analyzed in duplicate. Values represent the arithmetic average of duplicate analyses.

[b] POHC's per RCRA Appendix VIII list (May 1980).

ND = not detected (concentration is below detection limit).

2.6.1 Fuel Feed

The boiler is normally cofired with a purge thinner originating from the purging of paint spray guns. Table 17 summarizes the typical composition of the purge thinner. The firing rate is generally limited to approximately 31 ml/s (30 gph) and automatically shuts off when the boiler steam load falls below 3.8 kg/s (30,000 lb/hr). For this test, the cutoff point was lowered to 2.5 kg/s (20,000 lb/hr). The thinner was spiked with trichloroethylene, carbon tetrachloride, and chlorobenzene at the solvent tanks prior to cofiring. The waste paint thinner was kept mixed by continuous recirculation. During the last cofiring test it was necessary to dilute the waste by adding thinner to raise the level of waste in the hold tank to the level of the transfer pump intake.

2.6.2 Boiler Operation

Prior to this test program, the boiler had been taken down to replace the refractory in the throat. Since that time, it had been firing natural gas as the primary fuel. However, the oil guns and diffuser were not properly repositioned after the repair. Four tests were conducted: a baseline (fuel oil only) and three cofired tests. The burner misalignment caused the lower oil gun to coke over and shut down the boiler after the second cofired test and the upper oil gun to shut the boiler down again toward the end of the last cofired test. For the first part of the last test, the lower oil gun was inserted further into the boiler. After the second upset, the upper oil gun was also inserted further (8 to 10 cm (3 to 4 in.)). After these adjustments were made, there were no other problems with the boiler operation.

Table 18 summarizes the boiler operating conditions and fuel flows for each of the tests conducted. All four tests were conducted at a boiler steam load of 4.0 kg/s (32,000 lb/hr) which is about 50 percent of capacity. This operating level is typical for this unit. Excess combustion air of 60 to 66 percent are generally high for oil-fired boilers but typical of this boiler operation. There was a slight decrease in efficiency between the baseline and cofiring tests. Efficiencies calculated by the ASME heat loss method were 79.6 percent for the baseline and an average of 79.0 percent for the cofiring tests. This 0.6 percent efficiency loss is mostly attributable to the stack temperature, which increased from 236°C (458°F) to an average of 252°C (486°F). Waste fuel heat input ranged between 9 and 10 percent of the total heat input to the boiler.

2.6.3 Fuel Composition

Composite samples of the fuel oil and purge thinner were taken from the fuel feed lines prior to entering the boiler. A sample of the unspiked purge thinner was also taken. The fuel oil samples were composited for the entire test series and subjected to ultimate fuel analysis, as were the individual thinner samples. Two thinner samples were taken each day during the second and fourth tests. The results of the ultimate fuel analyses are presented in

TABLE 17. APPROXIMATE COMPOSITION OF PURGE THINNER -- SITE F

Compound	Approximate concentration (percent)
C_3-alkylbenzene	1
C_4-alkylbenzene	1
Aliphatic hydrocarbons	5
Butanedioic acid, dimethylester	5
Pentanedioic acid, dimethylester	15
Hexanedioic acid, dimethylester	10
Propenoic acid, octyl ester	5
Unidentified glycol-type compounds	40
Butylbenzyl phthalate	2.5
Other[a]	15.5
Total	100.0

[a] Unresolvable by GC and/or not extractable with methylene chloride.

TABLE 18. BOILER OPERATING CONDITIONS -- SITE F

Parameter	Test 1 baseline	Test 2 cofire	Test 3 cofire	Test 4 cofire
Steam flow, kg/s	4.0	4.0	4.0	4.0
(1,000 lb/hr)	(32)	(32)	(32)	(32)
Air flow, kg/s	4.9	5.2	5.2	4.8
(1,000 lb/hr)	(39)	(41)	(41)	(38)
Excess air, percent	66	59	63	65
Oil flow, ml/s	251	215	220	210
(gph)	(239)	(204)	(209)	(200)
Thinner flow, ml/s	0	28	35	30
(gph)		(27)	(33)	(29)
Furnace draft, Pa	-19	-17	-16	-20
(in. H_2O)	(-0.075)	(-0.067)	(-0.065)	(-0.08)
Total heat input, MW	10.7	10.4	10.4	9.8
(million Btu/hr)	(36.5)	(35.5)	(35.7)	(32.6)
Thinner heat input, percent of total	0	8.7	10.1	8.9
Volumetric heat release rate, kW/m^3	111	108	109	103
(Btu/hr-ft^3)	(10,800)	(10,500)	(10,500)	(9,600)
Moisture in flue gas, percent	8.6	8.6	9.2	10.0
Efficiency, percent[a]	79.6	79.0	78.7	79.2

[a] By ASME heat loss method.

Table 19. The variation in the thinner chlorine concentrations with time is attributed to insufficient mixing in the thinner tank.

Waste fuel samples were collected during each cofiring test for subsequent laboratory analysis. GC/MS was used to measure the concentration of the chlorinated organics TCE, CCl_4, and Cl_ϕ used to spike the purge thinner waste fuel at the site. Since these compounds are listed in RCRA Appendix VIII, measurements of these emissions and quantification of their DRE's was the primary objective of this test program. DRE's for toluene (also listed in RCRA Appendix VIII) and ethylbenzene were also determined through analysis of waste fuel concentrations and emission rates.

Table 20 summarizes the concentration of these organic compounds in milligrams per milliliter for each test. Each thinner sample consisted of composited 20 ml samples collected hourly. Except for test 4, two different composites were taken and analyzed separately. The second sample of this test corresponds to the fuel burned during actual volatile organic sampling. As was previously discussed, the feed tank was not well mixed and the concentration of chlorinated organics as observed from the thinner sample, changed with time. Toluene and ethylbenzene were the only volatile organics normally present in the purge thinner.

2.7 SITE G

The test unit was a Johnston modified three-pass wetback scotch marine packaged firetube boiler with a maximum heat input capacity of 14.7 MW (50 million Btu/hr) and a maximum saturated steam pressure of 1.75 MPa (250 psig). The firebox, first pass, has an approximate volume of 6.4 m^3 (226 ft^3) and a heating surface of approximately 20 m^2 (220 ft^2). This boiler was modified to allow incineration of highly halogenated hydrocarbons without severe corrosion which normally accompanies such firing practices. Major modifications included derating the firing capacity to 9.53 MW (32.5 million Btu/hr), changing to a negative draft from a positive pressure and several internal tube and baffle modifications to attain prescribed gas and surface temperature profiles. In addition, the boiler was retrofitted with two scrubber columns in series. The first scrubber column is used to recover the halogen while the second column utilizes a caustic to minimize residual acid emissions. This technology is patented.

The modified boiler, commonly referred to as thermal heat recovery oxidizer (THROX), is capable of firing natural gas and halogenated hydrocarbons in both liquid and gaseous form. Liquid hydrocarbons are injected with a single-air atomized nozzle located in the center of the natural gas ring. After a startup heating period on natural gas the boiler can operate entirely on halogenated hydrocarbons provided the hydrocarbons contain a minimum heating value of about 14,000 kJ/kg (6,000 Btu/lb). The feed can be less than 14,000 kJ/kg (6,000 Btu/lb) when cofired with natural gas, while the amount of halogen can be as high as 80 percent by weight.

Corrosion in the boiler is minimized by maintaining the temperature of metal surfaces exposed to combustion products in the range of 200° to 250°C

TABLE 19. FUEL ANALYSIS -- SITE F

Composition,[a] percent by weight	No. 6 fuel oil	Unspiked thinner	Test 2 spiked thinner	Test 3 spiked thinner	Test 4 spiked thinner
Carbon	86.80	67.15	67.78	65.64	64.29
Hydrogen	10.67	10.00	10.52	10.02	9.83
Nitrogen	0.41	2.09	0.87	0.58	0.71
Sulfur	0.87	<0.05	<0.05	<0.05	0.12
Chlorine	0.12	0.22	1.75	4.18	6.40
Oxygen (by difference)	1.03	18.07	16.91	18.07	17.23
Ash	0.03	2.26	1.23	1.07	0.99
Moisture	0.07	0.21	0.44	0.44	0.45
Higher heating value, kJ/kg (Btu/lb)	43,580 (18,751)	33,421 (14,380)	33,374 (14,359)	32,006 (13,771)	31,035 (13,351)
Specific gravity	0.9795	0.9377	0.9315	0.9426	0.9536

[a] Dry basis.

TABLE 20. VOLATILE ORGANIC COMPOSITION OF THINNER -- SITE F

Compound, mg/ml	Unspiked thinner	Test 2[a]	Test 3	Test 4	Test 4[a]
RCRA Appendix VIII					
Carbon tetrachloride	<1	20.8	29.8	30.0	29.5
Trichloroethylene	<1	7.8	48.6	61.4	49.2
Chlorobenzene	<1	1.29	5.6	5.8	3.5
Toluene	13.75	10.2	11.8	8.7	4.6
Other					
Ethylbenzene	<1	0.9	1.05	0.7	0.46

[a] Taken during volatile organic sampling run.

(390° to 480°F). In addition to boiler modification, this is accomplished by modulating heat input and steam pressure resulting in maximum firebox (first pass) outlet gas temperature of 1,100°C (2,000°F). Typically, gas temperatures in the firebox range between 1,300° and 1,400°C (2,400° and 2,600°F) with a gas residence time in the range of 0.3 to 0.5 sec.

2.7.1 THROX Feed

The typical THROX feed composition at this site is summarized in Table 21. Of the compounds in the feed, only bis(2-chloroisopropyl)ether and epichlorohydrin are RCRA Appendix VIII listed. To this mixture, carbon tetrachloride was added to extend the range of compounds of interest to be measured in this test program. The mixture was contained in a single mixing tank supplying the boiler for 100 percent of the fuel.

2.7.2 THROX Operation

The test program consisted of three tests with the THROX system operating on 100-percent chlorinated organics. Table 22 summarizes the operating conditions of the boiler and the two individual scrubbers during each test. Since the three tests were meant to be repetitive, the operation of the THROX system was generally constant throughout the test program. The data presented in Table 22 represent the arithmetical average of instantaneous readouts taken at about half-hour intervals.

TABLE 21. TYPICAL THROX FEED COMPOSITION -- SITE F

Component	Composition (percent)
Bis(2-chloroisopropyl)ether	40.7
Propylene dichloride	30.7
Epichlorohydrin	17.2
Propylene chlorohydrin	5.4
Trichloropropylene	3.2
Dichloropropylene	1.4
Propionaldehyde	1.4
Higher heating value, kJ/kg (Btu/lb)	21,500 (9,250)
Specific gravity	1.20

Average saturated steam production ranged from 1.74 to 1.91 kg/s (13,800 to 15,100 lb/hr) based on the condensate flowrate to the boiler. This steam production corresponds to an energy output in the range 4.10 to 4.54 MW (14.0 to 15.5 million Btu/hr). The average firing rate of the chlorinated organic feed was constant for each test at about 215 ml/s (3.43 gpm) corresponding to a total heat input of about 5.16 MW (17.6 million Btu/hr).

Excess oxygen in the flue gas generally ranged from about 8 to 9 percent as measured by the test site instrumentation at the boiler outlet. These excess O_2 levels correspond to excess combustion air of about 65 percent.

2.7.3 Feed Composition

Table 23 summarizes the composition of the THROX feed by ultimate analyses of samples collected during each of the three tests. The values are the average of three separate analyses performed for test 1 and two separate analyses for each of the two remaining tests. Each sample represents a composite of five individual samples each of 100 ml. Nitrogen, sulfur ash, and moisture in the feed were generally negligible. Combined, they account for less than 0.5 percent of the composition. Chloride (Cl^-) concentration ranged from about 36 to 48 percent with all but one sample having Cl^- concentration greater than 40 percent. The variation in Cl^- analysis results, by as much as 15 percent from the average, indicates that the

TABLE 22. SUMMARY OF THROX OPERATING CONDITIONS -- SITE G

Parameter	Test 1	Test 2	Test 3
Boiler steam and feedrates			
Condensate flowrate, l/s (gpm)	1.73 (27.7)	1.88 (30.1)	1.89 (30.3)
Feed firing rate, ml/s (gpm)	216 (3.43)	216 (3.43)	214 (3.40)
Heat input, MW (million Btu/hr)	5.23 (17.8)	5.02 (17.1)	5.26 (17.9)
Volumetric heat release rate kW/m^3 (Btu/hr-ft^3)	820 (79,000)	780 (76,000	820 (79,000)
Thermal efficiency, percent[a]	81.9	83.2	83.1
Combustion air and boiler pressure drop			
Atomizing air flowrate, kg/s (lb/hr)	73.0 (579)	70.9 (562)	68.1 (540)
Outlet flue O_2 concentration, percent	7.9	7.8	9.1
Flue pressure drop across boiler, kPa (in. H_2O)	1.33 (5.3)	1.34 (5.37)	1.32 (5.29)
Boiler flue gas temperatures			
Firebox out (first pass) 1, °C (°F)	902 (1,660)	891 (1,640)	888 (1,630)
Firebox out (first pass) 2, °C (°F)	870 (1,600)	864 (1,590)	856 (1,570)
Second pass 1, °C (°F)	321 (574)	300 (572)	299 (570)
Second pass 2, °C (°F)	284 (540)	282 (540)	280 (536)
Boiler out (third pass), °C (°F)	223 (433)	221 (430)	221 (430)
Recovery scrubber column			
Inlet water flowrate, l/s (gpm)[b]	5.3 (84)	5.2 (82)	5.2 (82)
Flue gas temperature inlet (bottom) °C (°F)	635 (146)	61.9 (143)	61.8 (143)
Flue gas temperature outlet (top), °C (°F)	39.1 (102)	35.0 (95)	35.8 (96)
HCl caustic scrubber column			
Inlet water flowrate, l/s (gpm)	9.94 (159)	10.4 (166)	9.81 (157)
Caustic flowrate, ml/s (gpm)	156 (2.5)	188 (3.0)	156 (2.5)
Discharge pH	9.0	9.0	9.0

[a] Based on ASME heat loss method.
[b] Calculated of inlet and outlet water flowrates. Not measured value.

TABLE 23. FEED ULTIMATE ANALYSIS -- SITE G

Composition, percent by weight	Test 1	Test 2	Test 3
Carbon	40.16	37.63	37.04
Hydrogen	6.91	6.91	6.37
Nitrogen	0.28	0.2	0.2
Sulfur	0.06	0.05	0.05
Chlorine	42.91	45.03	41.83
Oxygen (by difference)	9.64	11.24	14.54
Ash	0.002	0.003	0.004
Moisture	0.19	0.019	0.22
Higher heating value, kJ/kg (Btu/lb)	21,066 (9,083)	20,250 (8,730)	21,150 (9,112)
Specific gravity	1.1449	1.1448	1.1454

concentration of the various chlorinated compounds was probably changing; this is also reflected by the change in heating value of the feed.

GC/FID results of the organic composition of the feed are shown in Table 24. The compound concentrations varied considerably more than the average values indicate. For example, the bis(2-chloroisopropyl)ether concentration ranged from 399 to 544 mg/ml with both extremes observed during test 1.

2.8 SITE H

The boiler at site H is a Combustion Engineering (CE) VU-40 pulverized coal-fired boiler built in 1975, with a rated steam capacity of 32 kg/s (250,000 lb/hr) of superheated steam at 4.2 MPa (600 psig) and 393°C (740°F). This requires a heat input of approximately 100 MW (340 million Btu/hr). The furnace has a surface area of 1,310 m^2 (14,100 ft^2) with 515 m^2 (5,540 ft^2) of waterwall area and an estimated volume of 520 m^3 (18,400 ft^3). This results in a waterwall surface heat release rate of 194 kW/m^2 (61,400 Btu/ft^2) and a volumetric heat release rate of 190 kW/m^3 (18,500 Btu/ft^3) at maximum heat input. This tangentially fired boiler is

TABLE 24. THROX FEED ANALYSIS RESULTS[a] -- SITE G

Compound mg/ml	Test 1	Test 2	Test 3
Bis(2-chloroisopropyl)ether	495	505	509
1-chloro-2-propanol and t-1,3-dichloropropylene[b]	421	438	496
Epichlorohydrin	177	188	207
Carbon tetrachloride	44	45	47
Propionaldehyde	0.98	0.88	0.97
Cis-1,3-dichloropropylene	<1.0	<1.0	<1.0

[a] Analyses performed by GC/FID technique.
[b] Coeluting compounds.

equipped with three levels of pulverized coal burners in each furnace corner. The three levels are separated by two levels of steam-atomized oil burners. Generally, organic wastes are injected into the furnace by means of one or more of these oil burners. Typical steam loads are 32 kg/s (250,000 lb/hr), which is the rated steam capacity of the boiler. Primary and secondary combustion air is preheated by means of a regenerative air preheater. The unit is equipped with a cold side electrostatic precipitator (ESP) for flyash control. Flyash is collected and removed from the hopper continuously via a pneumatic system. From the ESP, the flue gas is imparted to a 46m (150-ft) brick stack via an induced draft fan.

2.8.1 Fuel Feed

Several organic waste streams are produced and incinerated in the boilers at this site. Firing rates of these waste streams are generally between 190 and 440 ml/s (3 and 7 gpm) when boiler loads exceed 19 kg/s (150,000 lb/hr). The waste stream of interest was crude methyl acetate available in a 5,700-liter (1,500-gal) tank. The methyl acetate was artificially spiked with chlorinated organic compounds, namely carbon tetrachloride (CCl_4), chlorobenzene ($Cl\phi$), and 1,1,1-trichloroethane (1,1,1-TCA). The mixture of methyl acetate and chlorinated compounds was prepared as follows:

- 208 liter (55 gal) of CCl_4
- 208 liter (55 gal) of $Cl\phi$

- 208 liter (55 gal) of 1,1,1-TCA
- 5,034 liter (1,330 gal) of methyl acetate

This mixture was prepared by adding one 208-liter (55-gal) drum of each of the chlorinated compounds to the methyl acetate to bring the total mixture to 5,680 liter (1,500 gal). One such mixture was prepared for each of the three scheduled cofiring tests.

2.8.2 Boiler Operation

Four tests were performed: one baseline and three cofire. All tests were performed with the boiler set on manual control. A heat output of 31 kq/s (246,000 lb/hr) of steam was maintained. No boiler upsets or transients were recorded. For test 1, the boiler was operated with pulverized coal (generally eastern Kentucky or south West Virginia bituminous) only. Furnace excess air and soot blowing cycles were typical for this firing condition. Tests 2 through 4 were the cofiring tests. Table 25 summarizes the boiler operating conditions. The chlorinated methyl acetate firing rate varied from 2.5 to 4.4 ml/s (2.4 to 4.2 gpm). One steam-atomized oil burner was used to input the waste which accounted for about 2 to 4 percent of the total heat input to the boiler.

2.8.3 Fuel Composition

Ultimate analyses of the waste fuel and coal are presented in Table 26. The coal composition represents the average of samples collected during each of the four tests. The waste fuel composition represent averages of duplicate analyses of composite samples.

Table 27 presents the average POHC concentration in the methyl acetate waste fuel. The combined concentration of carbon tetrachloride, chlorobenzene, and 1,1,1-trichloroethane ranged from about 8 percent for test 2 to 16 percent for test 4. Methyl acetate accounted for the remaining organic material. Chlorinated POHC's produced a HCl emission rate of 0.026 kg/s (210 lb/hr).

2.9 SITE I

The boiler tested at site I was a Foster Wheeler type AG252, forced draft, bent water tube boiler, with a Peabody-2 burner. At peak load it can deliver 7.8 kg/s (62,000 lb/hr) of saturated steam at 1.2 MPa (175 psi). The unit was installed in 1960 and originally designed to burn natural gas or fuel oil. The furnace has a volume of 40.5 m^3 (1,430 ft^3) and a waterwall area of 76.2 m^2 (820 ft^2). At maximum heat input, this results in a volumetric heat release rate of 520 kW/m^3 (50,000 $Btu/hr\text{-}ft^3$) and a surface heat release rate of 277 kW/m^2 (88,000 $Btu/hr\text{-}ft^2$). It is currently modified to fire waste fuel gas (largely methane) in combination with small amounts of organic liquid aniline waste. The boiler was not fitted with an air pollution control device.

TABLE 25. BOILER OPERATING CONDITIONS -- SITE H

Boiler parameter	Test 1 baseline	Test 2 cofire	Test 3 cofire	Test 4 cofire
Steam				
Steam flow, kg/s (10^3 lb/hr)	31.0 (246)	31.4 (249)	31.4 (249)	31.1 (247)
Coal flow, kg/s (lb/hr)	2.94 (23,400)	2.83 (22,500)	2.76 (21,900)	2.76 (21,900)
Waste solvent flow, ml/s (gpm)	0	2.5 (2.4)	4.4 (4.2)	2.6 (2.5)
Total heat input, MW (million Btu/hr)	93.5 (319)	93.5 (319)	93.5 (319)	92.9 (317)
Waste heat input, percent of total	0	2.4	4.26	2.81
Volumetric heat release rate, kW/m^3 (Btu/hr-ft^3)	180 (17,400)	180 (17,400)	180 (17,400)	179 (17,300)
Numbers of burners firing	4	4	4	4
Boiler out O_2, percent	3.4	3.5	3.4	3.4
Boiler efficiency, percent	86.9	87.4	87.4	86.8
Moisture in flue gas, percent	8.6	7.8	7.6	6.6
Furnace pressure, Pa (in. H_2O)	-145 (-0.59)	-150 (-0.6)	-150 (-0.6)	-134 (0.54)
Air heater outlet temperature, °C (°F)	293 (559)	297 (566)	303 (578)	297 (567)
Air heater gas inlet temperature, °C (°F)	396 (745)	399 (750)	404 (759)	383 (722)
Air heater gas outlet temperature, °C (°F)	174 (345)	181 (357)	185 (365)	178 (353)
Stack temperature, °C (°F)	166 (330)	167 (333)	171 (340)	168 (335)

TABLE 26. ULTIMATE FUEL ANALYSIS -- SITE H

	Coal	Waste fuel		
Composition, percent by weight	Test 1 to Test 4	Test 2	Test 3	Test 4
Carbon	77.4	34.0	33.6	36.8
Hydrogen	4.9	6.5	6.2	7.1
Nitrogen	1.85	0.4	0.4	0.3
Sulfur	0.725	0.01	0.01	<0.01
Chlorine	0.10	5.67	9.65	9.75
Oxygen	5.4	45.8	54.5	46.4
Ash	9.74	0.0009	0.0018	0.0007
Moisture	1.27	13.3	5.30	9.35
Higher heating value, kJ/kg (Btu/lb)	32,250 (13,875)	15,400 (6,630)	15,300 (6,565)	16,700 (7,171)

[a] Average of samples taken during each test.

TABLE 27. WASTE FUEL POHC CONCENTRATION[a] -- SITE H

Compound, mg/ml	Test 2	Test 3	Test 4
Carbon tetrachloride	26.9	44.1	49.5
Chlorobenzene	26.2	30.3	48.7
1,1,1-trichloroethane	20.3	36.0	39.5

[a] Analysis by GC/MS

Combustion air, natural gas, and liquid waste are fed to the combustion zone through two parallel, circular burner ports. The combustion air enters the ports in advance of the fuel gas through adjustable registers. The fuel gas is injected through a ring of spuds near the end of the circular burner port. Both the upper and the lower burners can be fitted with organic liquid waste steam atomizing guns. The gun is located on the axis of the burner port and extends to a point just beyond the diffuser ring and at the gun tip. The lower burner was used to fire the liquid aniline waste material burned during this test program while the upper waste fuel gun was removed. During the baseline tests with only fuel gas being fired, the guns were removed from both burners. Removal or replacement of the guns does not affect the presence or position of the diffuser ring.

The combustion air controls on this boiler have been modified to achieve a staged combustion effect during periods of liquid waste firing. Staged combustion is achieved by partially closing the air register to the lower burner which promotes fuel-rich combustion in the lower flame zone (where the bulk of the nitrogenous liquid waste is combusted) and lean combustion in the upper flame zone. Mixing and secondary combustion takes place downstream of the established flame zone. The O_2 trim control, which measures and responds to excess O_2 in the flue gas, maintains the total airflow to the boiler at the level required to meet stoichiometric and excess air requirements for efficient combustion. Under normal conditions the boiler operates in a staged combustion mode whenever liquid waste material is being fired. Operator personnel indicated that the air split between the upper and lower burner under these conditions is about 65/35, respectively. When the liquid waste feed is discontinued and fuel gas alone is fired, the air register automatically returns to the fully open position.

2.9.1 Fuel Feed

The liquid waste fired in this test was a mixture of nitrobenzene, aniline, benzene and water from an aniline production plant. This waste fuel was spiked with a mixture of carbon tetrachloride, chlorobenzene, trichloroethylene and toluene. Table 28 summarizes the composition of the spiked waste.

The liquid waste and solvents were combined in an unbaffled tank trailer with a total capacity of about 11,000 liters (3,000 gallons). Mixing was accomplished by hauling the trailer about the plant grounds at slow speed and repeatedly making abrupt stops. This action was continued for about two hours to ensure complete mixing of the liquid waste and solvents. Following mixing, the trailer was parked and connected to the existing system feeding liquid waste to the boiler.

Spiked liquid waste was drawn from the stationary tank trailer and pumped through roughly 100 meters (300 ft) of electrically heated and insulated pipe to the boiler house. The normal liquid waste tank was disconnected from the system and blanked during the test. In addition, a small recirculation line (2-cm (3/4-in.) pipe) from the pump discharge to the tank trailer and a sampling station were installed. At the boiler house, the

TABLE 28. COMPOSITION OF THE SPIKED ANILINE WASTE -- SITE I

Compound	Quantity mixed, liters (gal)		Approximate mixture composition (% by weight)
Organic solvents	617	(163)	10.4
Carbon tetrachloride	115	(30.5)	(2.6)
Trichloroethylene	123	(32.5)	(2.6)
Toluene	212	(50)	(2.6)
Chlorobenzene	167	(44)	(2.6)
Liquid waste material[a]			89.9
Aniline	≈57	(≈15)	(≈1)[a]
Benzene	≈57	(≈15)	(≈1)[a]
Nitrobenzene	≈5,155	(≈1,362)	(≈88)[a]

[a] Estimate based on preliminary gas chromatography analysis of the spiked liquid waste material

liquid waste feed was passed through a coarse screen (≅1 in. square mesh) and introduced to the burner system. Flow and line pressure measurements are made at the boiler house.

With all components operating properly, the waste feed system was capable of delivering about 130 ml/s (2 gpm) to the boiler. However, due to pump failures and other operating difficulties, the system was barely able to deliver the 38 ml/s (0.6 gal/min) flow required for the tests. In all, four different waste feed pumps were installed during the 30 hours of liquid waste tests. Damage to the pumps was attributed to grit and/or tar-like substance in the waste.

2.9.2 Boiler Operation

Four tests were performed: two with staged combustion and two with unstaged combustion. One staged and one unstaged test were cofired with waste fuel and the other two were fired with natural gas only. Table 29 summarizes boiler operating conditions.

The boiler was set to operate at 5.0 kg/s (40,000 lb/hr) of steam and 1.5 percent excess O_2. Actual steam rate varied from 4.9 kg/s (39,100 lb/hr) to 5.2 kg/s (41,200 lb/hr) average values for the tests. The boiler had been removed from normal service during the tests and therefore was not subject to the load swings common during normal demand load operation. For the most

TABLE 29. BOILER OPERATING CONDITIONS[a] -- SITE I

Boiler parameters	Baseline unstaged combustion[b] Test 1	Liquid waste staged combustion[c] Test 2	Baseline staged combustion[c] Test 3	Liquid waste unstaged combustion[b] Test 4
Steam flow, kg/s (lb/hr)	5.1 (40,300)	5.1 (40,600)	5.0 (39,800)	5.1 (40,100)
Natural gas flow, l/s (scfm)	362 (768)	329 (697)	361 (764)	330 (699)
Waste fuel flow, ml/s (gpm)	0	38 (0.6)	0	38 (0.6)
Total heat input, MW (million Btu/hr)	14.2 (48.3)	13.8 (47.0)	13.9 (47.4)	13.7 (46.9)
Volumetric heat release rate, kW/m^3 ($Btu/hr\text{-}ft^3$)	351 (33,800)	341 (32,900)	343 (33,100)	338 (32,800)
Furnace pressure, kPa (in. H_2O)	(1.3)	(1.5)	(1.4)	(1.4)
O_2 in flue gas, percent by volume	1.7	2.6	2.4	2.6
Waste fuel heat input, percent of total	0	8.2	0	8.2
Flue gas temperature, °C (°F)	241 (466)	242 (468)	243 (469)	244 (471)

[a] Average values for three test runs.

[b] Unstaged combustion means that the air registers for the upper and lower burners are open by the same amount and the combustion air split between the upper and lower burners is about 50/50, respectively.

[c] Staged combustion means that the air register to the lower burner is restricted and that the air split between the upper and lower burners is about 65/35, respectively.

part, the steam produced from the boiler was vented. Isolation of the boiler enabled consistent operation but prevented exact duplication of normal operation. Excess O_2 varied from 1.9 percent to 2.7 percent test average values. It was found, except for the first two samples from test 1 during pretest operation, that operating at the 1.5 percent O_2 level resulted in high CO concentrations. Thus, operating settings were revised to maintain an O_2 level to keep CO in the range of 300 to 500 ppmv.

Heat was supplied by the fuel gas (natural gas plus process waste gases) during the background test sets. This fuel was supplemented with the liquid waste during the hazardous waste test sets. Total heat inputs averaged 14.2 MW (48.3 million Btu/hr) during the background tests and 13.8 MW (47.0 million Btu/hr) during the cofire tests. The liquid hazardous waste supplied 8.2 percent of the total input energy for the cofire tests.

2.9.3 Fuel Composition

The waste was spiked with equal weights of the four compounds (carbon tetrachloride, trichloroethylene, chlorobenzene and toluene). However, analyses of samples collected during the tests show a wide divergence from equal weights. Table 30 summarizes these analytical results. Toluene and chlorobenzene showed the expected concentrations but carbon tetrachloride and trichloroethylene showed about one half of the expected concentrations. It may be significant to note that since the latter two compounds are the most volatile some amounts might have been lost in mixing, storing, or preparing composite samples. The fuel composition remained constant between tests 2 and 4.

2.10 SITE J

The boiler tested at site J was a North American model 3200X, three-pass, firetube packaged boiler with a maximum heat input of 2.5 MW (8.4 million Btu/hr) and a rated steam pressure of 1.0 MPa (150 psig). The unit uses a North American oil burner with an oil capacity of 16.8 to 63.6 ml/s (16.0 to 60.5 gph) at 0.52 to 0.83 MPa (75 to 120 psig). The furnace has a radiant surface area of 8.46 m^2 (91.1 ft^2) and volume of 1.45 m^3 (51.1 ft^3) with 33.3 m^2 (358 ft^2) of heat exchange area. This results in a surface heat release rate of 300 KW/m^2 (92,000 $Btu/hr\text{-}ft^2$) and a volumetric heat release rate of 1.7 MW/m^3 (164,000 $Btu/hr\text{-}ft^3$) at maximum heat input.

It was discovered that the unit would operate within a very narrow range of excess air levels. Below the minimum excess air used in the tests (17 percent), combustion was incomplete and smoke formed. The air controller can easily be adjusted so that too little excess air would never occur during operation. Above the maximum excess air used in the tests (53 percent) the flame becomes unstable and flame scanner controls automatically shut down the fuel flow.

TABLE 30. POHC COMPOSITION OF WASTE FEED[a] -- SITE I

Composition, percent by weight		Test 2	Test 4
Carbon tetrachloride		1.7	1.8
Trichloroethylene		1.7	1.8
Nitrobenzene		82.9	83.9
Monochlorobenzene		3.2	3.2
Aniline		2.6	2.1
Benzene		1.7	1.8
Toluene		3.4	3.5
Higher heating value,	kJ/kg (Btu/lb)	24,700 (10,620)	24,700 (10,630)
Specific gravity		1.1973	1.1971

[a] From GC/MS analysis. Corrected for water measured in samples.

2.10.1 Fuel Feed

The waste fuel consisted of a blend of chemicals which were representative of a hazardous waste. Reagent grade carbon tetrachloride, technical grade chlorobenzene, and technical grade trichloroethylene were carefully weighed to the desired amounts and added into the fuel tank. The tank was then topped off with nitration-grade toluene (>99 percent pure). Although the fuel tank was cleaned prior to the first test, it was noted that this mixture of clear chemicals took on a transparent but brown color. It is believed that a residue of fuel oil in the pipelines of the system caused this coloration. Even in the worst case, an insignificant amount of fuel oil contaminated the test chemicals.

The burner of the test unit is designed to fire on either gas or oil, but normally burns natural gas. Therefore, the fuel oil firing system could be cleaned, adjusted, and used to fire test blends of liquid chemicals without interrupting normal operation of the boiler. The fuel oil system consists of a 1,000-gal cylindrical tank, a pump, mechanical Teflon seals, an atomizing air compressor, and a spray nozzle. The storage tank is plumbed to a nearby tank farm to permit filling the 1,000-gal tank from long-term storage. Approximately 90 percent of the pumped fuel is returned from the boiler to the storage tank when the boiler is firing at full capacity. This recycling mixes the contents of the tank.

2.10.2 Boiler Operation

Table 31 summarizes the boiler operating conditions and fuel and air flows for the tests conducted. A total of six tests were performed. The waste fuel feedrate varied from an average 0.031 kg/s (244 lb/hr) at half load conditions to an average 0.056 kg/s (445 lb/hr) at full load. The range of feedrates at half load conditions was 0.025 to 0.033 kg/s (185 to 262 lb/hr); at full load the range was 0.048 to 0.063 kg/s (377 to 498 lb/hr). The stoichiometric air-to-fuel ratio did not differ significantly among the test conditions, since toluene was always the major fuel constituent at 97 to 98 weight percent.

Excess air levels ranged from 16.9 to 37.6 percent above stoichiometric for test conditions 1, 2, 3, and 6. In test conditions 4 and 5, a deliberate attempt was made to modify the air supply to the boiler, resulting in excess air levels of 40 to 53 percent above stoichiometric at full and half load, respectively.

To provide controllable test conditions, the test boiler was operated at steady state for 10 to 12 hr/day, venting steam when necessary. During the remaining hours of each test day, the test boiler was returned to firing natural gas in its normal cyclic mode. Fuel was blended the evening before each test day. The chemicals were mixed by recirculating overnight.

Before each test began, the boiler was fired on natural gas for at least half an hour. On the first day of testing, a service engineer from North American Manufacturing tuned the boiler and assured that it was operating properly.

2.10.3 Fuel Composition

The compositions of the fuels (by weight) burned during this test program were determined from the individually measured quantities of POHC's blended together to make the test fuels. Two different fuel blends were prepared. Blend no. 1 consisted of approximately 0.5 percent carbon tetrachloride, 1.0 weight percent trichloroethylene, and 0.5 percent chlorobenzene in a toluene matrix. Blend no. 2 differed only in that the trichloroethylene concentration was increased to approximately 2.0 percent, while toluene was reduced to approximately 97 percent.

Since these fuel blends were prepared separately for each of the six test conditions, some small differences occurred in their composition over the course of the field test. Tables 32 and 33 summarize the carbon, hydrogen, and chlorine composition and POHC concentration, respectively, for the fuel blends burned during each of the six test conditions. The ultimate analysis was determined by calculation from the fuel composition data and the elemental composition of the POHC's. The only major difference in ultimate

TABLE 31. BOILER OPERATING CONDITIONS -- SITE J

	Fuel blend no. 1				Fuel blend no. 2	
Boiler parameter	Test 1 half load	Test 2 full load	Test 4 full load (high EA)	Test 5 half load (high EA)	Test 3 half load	Test 6 full load
Waste fuel flow, ml/s (gal/hr)	33.3 (31.7)	65.4 (62.2)	57.2 (54.4)	26.4 (25.2)	36.0 (34.2)	67.8 (64.4)
Total heat input[a], MW (million Btu/hr)	1.2 (4.3)	2.4 (8.3)	2.1 (7.3)	1.0 (3.4)	1.3 (4.6)	2.5 (8.7)
Excess air, percent	37.0	21.8	40.2	52.9	33.9	16.9
Volumetric heat release rate, kW/m^3 (Btu/hr-ft^3)	870 (84,000)	1,700 (160,000)	1,500 (140,000)	690 (66,500)	930 (90,000)	1,750 (170,000)
Boiler exit temperature, °C (°F)	183 (361)	273 (523)	263 (505)	192 (377)	209 (408)	264 (507)
Bulk furnace temperature, °C (°F)	1,310 (2,400)	1,370 (2,500)	1,370 (2,500)	1,370 (2,500)	1,310 (2,400)	1,370 (2,500)
Residence time, sec	0.58	0.32	0.32	0.67	0.55	0.32

[a] Based on estimated fuel heating value of 42,000 kJ/kg (18,000 Btu/lb).

TABLE 32. FUEL ULTIMATE ANALYSIS -- SITE J

	Fuel blend no. 1				Fuel blend no. 2	
Composition, percent by weight[a]	Test 1 half load	Test 2 full load	Test 4 full load (high EA)	Test 5 half load (high EA)	Test 3 half load	Test 6 full load
Carbon	89.89	89.91	89.96	89.95	89.25	89.24
Hydrogen	8.59	8.60	8.60	8.60	8.53	8.52
Chlorine	1.52	1.49	2.60	1.45	2.22	2.24
Higher heating value, kJ/kg (Btu/lb)	41,700 (17,960)	41,760 (17,970)	41,700 (17,950)	41,700 (17,940)	41,400 (17,780)	41,300 (17,770)
Specific gravity	0.882	0.881	0.881	0.881	0.887	0.887

[a] Calculated from fuel blend composition data and POHC chemical composition from Table 33.

TABLE 33. POHC'S COMPOSITION OF TEST FUEL -- SITE J

	Fuel blend no. 1				Fuel blend no. 2	
Composition, percent by weight	Test 1 half load	Test 2 full load	Test 4 full load (high EA)	Test 5 half load (high EA)	Test 3 half load	Test 6 full load
Toluene	97.88	97.91	97.99	97.94	97.01	96.97
Carbon tetrachloride	0.53	0.52	0.50	0.50	0.48	0.50
Trichloroethylene	1.07	1.05	1.01	1.01	2.00	1.99
Chlorobenzene	0.52	0.52	0.50	0.55	0.51	0.54

analysis values can be seen in the fact that the chlorine concentration of blend no. 2 is twice that of blend no. 1. The heating value and specific gravity of the fuel blends were determined from the fuel composition.

2.11 SITE K

The boiler tested at site K was a Combustion Engineering VU-10 balanced draft watertube boiler with a Peabody AT burner. The unit has a heat exchange area of 645 m^2 (6,936 ft^2), of which 47.2 m^2 (508 ft^2) is water wall area and a furnace volume of 64.5 m^3 (2,275 ft^3). The boiler has a rated heat input of 23 MW (75 million Btu/hr) where it can deliver 7.6 kg/s (60,000 lb/hr) of saturated steam at 178°C (353°F) at 0.86 MPa (125 psi). This results in a surface heat release rate of 490 kW/m^2 (150,000 Btu/hr-ft^2) and a volumetric heat release rate of 360 kW/ft^3 (33,000 Btu/hr-ft^3). This unit was not equipped with an air pollution control device.

2.11.1 Fuel Feed

Typical fuels burned are off-specification waste fuels in place of or cofired with no. 6 fuel oil. The fuels are fired in one of two feed systems depending on viscosity. Heavy high-viscosity fuels such as no. 6 oil and no. 6 oil/waste solvent blends are treated with additives and preheated. When 100 percent no. 6 oil is fired, the oil preheat temperature is typically held within the range of 93° to 105°C (200° to 220°F). The strained, preheated heavy oil is sent through a flow metering device and then to the burner, where it is atomized with steam and combusted. Light, low-viscosity fuel oil is sent through a flowmeter and then to the burner where it is mixed with atomizing air and combusted. A 70 percent no. 6 oil/30 percent waste solvent mixture was used for the cofire testing and preheated from 43° to 49°C (110° to 120°F).

The light oil mixture was prepared by adding carbon tetrachloride, trichloroethylene, and chlorobenzene to two small tankers containing a waste solvent mixture whose composition was unknown prior to and during the test program. Plant personnel estimated the volume of the tankers before spiking to be 17,500 and 14,700 liters (4,625 and 3,892 gal) for tankers I and II, respectively. The amounts of the spiking compounds added to the two waste solvent tankers are shown below, along with the estimated composition of the spiked mixtures.

	Tanker I			Tanker II		
Component	Amount added liters	(gal)	Volume % in light oil	Amount added liters	(gal)	Volume % in light oil
Carbon tetrachloride	53	(14)	0.30	45	(12)	0.31
Trichloroethylene	53	(14)	0.30	45	(12)	0.31
Monochlorobenzene	72	(19)	0.41	61	(16)	0.41

The waste solvent mixture in each tanker was recirculated thoroughly after addition of the spiking compounds to ensure that the spiking compounds were evenly distributed. The contents of the two tankers were also recirculated together.

During the test runs, the spiked waste solvent mixture was drawn from the tanker using one of the pumps in the light oil feed system while the contents of the tanker were internally recirculated using a second pump. The spiked waste solvent mixture was fed to the boiler using the light fuel oil supply system.

2.11.2 Boiler Operation

Two tests were performed: one baseline test with no. 6 oil and one cofire test with a heavy oil mixture consisting of approximately 70 percent no. 6 oil/30 percent waste solvents and a light oil mixture consisting of waste solvents spiked with a mixture of carbon tetrachloride, trichloroethylene, and monochlorobenzene. Table 34 summarizes the boiler operating conditions. During the baseline test, all four burners fired No. 6 oil. For the cofire test, two burners fired the heavy oil mixture and the remaining two fired the light oil mixture. The light oil mixture made up 52 percent of the waste flow on a volume basis for test 2.

The boiler load was maintained as close as possible to 6.07 kg/s (48,000 lb/hr) of steam during all test runs. The measured steam production rate varied by less than 2 percent within each run, and the mean steam production rate for the individual runs ranged from 6.07 to 6.19 Kg/s (48,000 lb/hr to 49,100 lb/hr). The O_2 content of the boiler flue gas was maintained as closely as possible to the minimum value while still resulting in low stack opacity.

2.11.3 Fuel Composition

Samples of the no. 6 oil used in test 1 and of the heavy and light oil mixtures used in test 2 were analyzed. The samples were individual run composites of samples taken every half hour during each run. The ultimate analysis of the heavy and light oil mixtures is shown in Table 35. API gravity measurements were made on site for each half hour spiked light oil sample during test 2 to verify that the feed was well mixed. The POHC composition of the fuels is shown in Table 36.

2.12 SUMMARY OF BOILER DESIGN, FUELS, AND OPERATION

Industrial boilers firing hazardous waste fuels were tested at 11 different sites. A total of 42 separate waste fuel firing tests were performed generally at typical boiler operating conditions. Most sites, with the exception of sites A, G, and J, also included one baseline test per site with the boiler firing a primary fossil fuel. These tests were performed to measure the background organic emissions attributable to fossil fuel combustion only. Three of the boilers were of firetube design, sites B, G, and J with operating capacities ranging from 2.5 to 12 MW (8.5 to

TABLE 34. BOILER OPERATING CONDITIONS -- SITE K

	No. 6 oil baseline	Cofire[a]
Boiler parameter	Test 1	Test 2
Steam flow, kg/s (10^3 lb/hr)	6.11 (48.5)	6.15 (48.8)
No. 6 oil or 70/30 oil/solvent flow, ml/s (gph)	406 (386)	225 (214)
Light solvent flow, ml/s (gph)	0	252 (240)
Total heat input, MW (million Btu/hr)	17.2 (58.7)	17.4 (59.2)
Light oil solvent heat input, percent of total	0	49.3
Volumetric heat release rate, kW/m^3 (Btu/hr-ft^3)	267 (25,800)	270 (26,000)
Number of burners firing	4	2/2
Boiler out O_2, percent	3.8	4.0

[a] 70 percent no. 6 oil/30 percent waste solvent and 100 percent waste solvent spiked with test mixture.

TABLE 35. ULTIMATE ANALYSIS OF FUEL -- SITE K

Composition[a], percent by weight	Test 1 no. 6 oil	Test 2 heavy oil mixture	Test 2 light oil mixture
Carbon	86.83	82.42	76.79
Hydrogen	10.70	11.20	10.96
Nitrogen	0.44	0.26	0.17
Chlorine	0.10	0.37	1.79
Oxygen (by difference)	1.17	5.43	10.16
Sulfur	0.71	0.44	0.06
Ash	0.05	0.08	0.06
Higher heating value, kJ/kg (Btu/lb)	42,935 (18,460)	42,703 (18,360)	39,772 (17,100)
Specific gravity	0.986	0.910	0.873
Water content, percent by volume	0.026	1.2	1.13

[a] Values are averages of three test runs.

TABLE 36. FEED ANALYSIS -- SITE K

Composition, percent by weight[a]	Test 1 no. 6 oil	Test 2 heavy oil mixture	Test 2 light oil mixture
Carbon tetrachloride	0	0	1.0
Trichloroethylene	0	0	0.8
Chlorobenzene	0	0	0.9
Toluene	0.05	2.8	1.2
Benzene	0	0.2	0.1
m&p-Xylene	0.2	4.6	4.0
o-Xylene	0.02	0.7	0.6
Phenol	0	0	23

[a] By GC/MS analysis.

40 million Btu/hr) heat input. The remaining eight test sites were watertube designs with heat input capacities ranging from 4.1 MW (14 million Btu/hr) for the wood-fired site A boiler to 100 MW (340 million Btu/hr) for the pulverized coal-fired site H boiler.

Table 37 summarizes the boiler design, operation, and fuels during each of the test programs. Typically, steady-state boiler operating conditions were sought during each test. However, several emission measurements were performed during unsteady boiler/burner conditions. These unsteady conditions occurred primarily at sites A, B, E, and F. The wood-fired design of the site A boiler is inherently unsteady in operations due to the nature of the fuel and its feed system. This boiler was also the least instrumented and therefore operating conditions could not be easily determined. Site B was the smallest of the boilers tested operating at about 30 percent of capacity. The waste was mostly (>90 percent) water and not homogeneous. This caused several feed problems and interruptions in the tests. At site E, the sensitivity of waste fuel cofiring on burner operation was clearly evident. Waste cofiring necessitated higher excess air levels and careful control of feed rates. Waste flow surges and improper waste gun orientation caused several smoke episodes. At site F, the improper position of fuel guns in the burner throats caused several upset conditions including burner nozzle coking and sudden flame-outs.

TABLE 37. BOILER SUMMARY

Site	Boiler type	Primary fuel(s)	Waste description	Emission control device	Operational conditions
A	Keeler CP 308-hp (10,000 lb/hr of steam) watertube boiler	Wood waste: chips, bark and sawdust	4 cofire tests ● Creosote sludge containing chlorinated aromatics including pentachlorophenol, phenol, naphthalene, and fluorene	Multiclone for particulate collection	Typical wood boiler operation with high excess air and high combustible emissions. Baseline fuel contaminated with creosote. Boiler poorly instrumented.
B	Cleaver-Brooks 250-hp (8,400 lb/hr of steam) firetube boiler	1 baseline test natural gas	3 cofire tests ● Alkyd waste water with paint resin containing toluene, xylenes, and several acids	None	Low load tests. Several waste feed problems caused by inefficient mixing of waste and plugging of screens. Fluctuations in waste feed flow.
C	Babcock & Wilcox 29-kg/s (230,000 lb/hr of steam) multiburner watertube	1 baseline test natural gas	3 cofire tests ● Phenolic waste containing phenol, alkylbenzenes, and long-chain aromatic and aliphatic hydrocarbons	None	Low boiler load and high excess air. No operational transients.
D	Babcock & Wilcox 11.4-kg/s (90,000 lb/hr of steam) multiburner watertube[a]	1 baseline test no. 6 oil	3 cofire tests ● Waste stream no. 1 -- Mixture of methanol xylenes and tetrachloroethylene 3 cofire ● Waste stream no. 2 -- Mixture of toluene and bis(2-chloroethyl) ether	None[b]	Burner problems experienced with waste stream no. 1. Waste feed interruption due to filter plugging. No transients with waste stream no. 2.

[a] Boiler originally stoker-coal fired converted to oil burning.
[b] Some particulate collected by existing hopper cavities.

(continued)

TABLE 37. CONTINUED

Site	Boiler type	Primary fuel(s)	Waste description	Emission control device	Operational conditions
E	Combustion Engineering 13.9-kg/s (110,000 lb/hr) of steam single burner packaged watertube	1 baseline test no. 6 oil and natural gas	1 cofire test • Waste stream no. 1 -- Mixture of methyl methacrylate, and fluxing oils 6 cofire test • Waste stream no. 2: waste stream no. 1 spiked with -- Carbon tetrachloride -- Chlorobenzene -- Trichloroethylene 1 cofire test • Waste stream no. 3 mixture of toluene and methyl methacrylate	None	Smoke emissions and transients experienced with spiked waste stream no. 1. Generally higher excess air required during cofiring. Smoke generation sensitive to orientation of waste fuel guns and surges in waste flowrates.
F	Babcock & Wilcox 7.6-kg/s (60,000 lb/hr of steam) multiburner watertube	1 baseline test no. 6 oil	3 cofire tests • Purge thinner containing mixed methyl esters, butyl cellosolve acetate, aromatic hydrocarbons, aliphatic hydrocarbons. Spiked with chlorobenzene trichloroethylene and carbon tetrachloride	None	Improper setting of burners caused several flame-nuts independent of waste feed.
G	Johnston modified firetube boiler 5.0 kg/s (40,000 lb/hr of steam or 1,200 hp). Thermal heat recovery oxidizer (THROX)[c]	None Natural gas used only for startup	3 primary firings • Mixture of chlorinated hydrocarbons containing up to 55 percent by weight chlorine. Major components: -- Bis(2-chloroisopropyl) ether -- Epichlorohydrin Spiked with carbon tetrachloride	Two chloride recovery/ removal water scrubber columns in series	Steady-state operation. No primary fuel burned.

(continued)

[c] Patented process for heat generation and chemical recovery of highly halogenated hydrocarbons.

TABLE 3-37. CONCLUDED

Site	Boiler type	Primary fuel(s)	Waste description	Emission control source	Operational conditions
H	Combustion Engineering tangential NSPS coal-fired boiler 3.2 kg/s (250,000 lb/hr) of superheated steam	1 baseline test Pulverized bituminous coal	3 cofire tests ● Crude methyl acetate. Spiked with trichloroethane, carbon tetrachloride and chlorobenzene	Cold side electrostatic precipitator	High boiler load with steady state operation. Low waste/coal heat input.
I	Foster Wheeler AG252 forced draft, bent tube boiler 7.8 kg/s (62,000 lb/hr of steam)	1 baseline test staged 1 baseline test unstaged natural gas	1 cofire staged test, 1 cofire unstaged test ● Liquid waste containing nitrobenzene, aniline benzene. Spiked with carbon tetrachloride, trichloroethylene, chlorobenzene and toluene	None	Nominal load. No significant boiler transients. Damage to waste feed pumps caused several pump replacements.
J	North American 3200X kg/s (200 hp) packaged firetube boiler	None	6 cofire tests with 2 different trichloroethylene concentrations ● Carbon tetrachloride, monochlorobenzene, trichloroethylene, and toluene	None	Half and full loads high and normal EA. No significant boiler transients or impacts.
K	Combustion Engineering VU-10 balanced draft, watertube boiler 7.6 kg/s (60,000 lb/hr) of steam	1 baseline test no. 6 oil	1 cofire test ● Light and heavy oil mixtures Spiked with carbon tetrachloride, trichloroethylene, and chlorobenzene	None	Nominal test load with no significant boiler operational transients.

Starting with site D, all waste fuels were artificially spiked to extend the number of POHC's present in the waste fuels, thus facilitating intrasource comparison of DRE results. The spiked mixture generally consisted of carbon tetrachloride, chlorobenzene, and trichloroethylene. At site H, 1,1,1-trichloroethane was substituted for trichloroethylene.

Table 38 summarizes size-specific engineering data on operating and boiler design variables that may have an effect on efficient POHC destruction. Heat release rates, both volumetric and surface, are based on the calculated heat input rate for each test. Heat release rates provide information of the relative bulk furnace temperatures and residence times between boiler designs. Bulk furnace temperatures and gas residence times were not parameters that were measured during these tests. Estimates for furnace temperatures and residence times were calculated based on general boiler engineering data and site-specific information. Although not to be considered accurate, the information is sufficient to provide a meaningful comparison between boilers. Longer residence times at higher furnace temperatures are likely to result in more efficient destruction for the same degree of fuel-air mixing, excess air, and waste characteristics. Boilers with furnace residence times of greater than 1 sec are the watertubes of sites A, C, D, F, H, I, and K. Of these, site A had the lowest test condition surface heat release rate. Firetubes have residence times generally much lower than 1 sec, with higher surface and volumetric heat release rates.

Waste fuel heat input ranged from less than 1 percent for site B to 100 percent for sites G and J. Site B waste fuel was contaminated water with an insignificant heating value. At sites G and J, the waste fuel accounted for all the heat to the boiler.

TABLE 38. SUMMARY OF BOILER OPERATION AND FUEL PARAMETERS

Site	Volumetric heat release rate, kW/m3 (10^3 Btu/hr-ft^3)	Waterwall surface heat release rate, kW/m^2 (10^3 Btu/hr-ft^2)	Bulk furnace temperature,[a] °C (°F)	Bulk furnace residence time,[a] sec	Primary fuel flowrate,	Waste fuel flowrate, ml/s (gal/hr)	Waste fuel heating value, kJ/kg (Btu/lb)	Waste heat input, percent of total
A	300 (29)	48 (16)	1,370 (2,500)	1.2	0.24 kg/s (1,950 lb/hr)	50 (48)	38,700 (16,700)	40
B	745 (72)	106 (34)	1,320 (2,400)	0.8	20.4 l/s (2,590 ft^3/hr)	34.3 (33.2)	30-180 (13-77)	<1
C	78 (7.5)	150 (48)	1,320 (2,400)	2.0	420 l/s (53,000 ft^3/hr)	257 (245)	38,500 (16,600)	38
D	230-400 (22-39)	100-180 (33-57)	1,370-1,430 (2,500-2,600)	1.1-1.3	0.18-0.51 kg/min (24-67 lb/hr)	190-270 (180-260)	20,600-42,000 (8,800-18,000)	18-48
E	380-480 (37-47)	24-32 (7.6-10)	1,480-1,590 (2,700-2,900)	0.8-1.1	204-354 l/s gas (430-750 ft^3/hr)	240-260 (220-240)	26,700-37,000 (11,500-16,000)	33-56
	380-770 (37-74)	24-49 (7.6-15)	1,480-1,590 (2,700-2,900)	0.5-1.0	0.21-0.62 kg/min oil (27-79 lb/hr)	195-260 (190-250)	24,500-27,300 (10,500-11,741)	19-43
F	114 (11)	104 (34)	1,370 (2,500)	2.0	0.19 kg/s (26 lb/hr)	30 (29)	32,500 (14,000)	9.0
G	820 (79)	262 (81)	1,300-1,400 (2,400-2,500)	0.3-0.5	0	215 (103)	21,000 (9,000)	100
H	180 (17)	183 (58)	1,370 (2,500)	2.0	2.8 kg/s (22,000 lb/hr)	160-270 (140-250)	16,500 (7,000)	2.4-4.3
I	340 (33)	181 (57)	~1,430 (~2,600)	1.8	330 l/s (12 ft^3/hr)	38 (36)	24,700 (10,600)	8.2
J	690-1,750 (65-170)	118-300 (37-95)	1,310-1,370 (2,400-2,500)	0.3-0.7	0	26-68 (25-64)	41,500 (17,900)	100
K	270 (26)	370 (117)	1,370 (2,500)	1.8	13 kg/min (1700 lb/hr)	250 (240)	40,400 (17,400)	65

[a] Not measured values

SAMPLING AND ANALYSIS PROTOCOLS

The primary objective of the test programs conducted for each site was to measure POHC input and flue gas emission rates to determine their destruction efficiency (DRE) and to identify products of incomplete combustion (PIC's). In addition to the organic sampling and analysis that was performed to determine POHC's DRE's and PIC formation, several other measurements were made to determine gaseous and particulate criteria emissions in the combustion products, organic and inorganic pollutants in liquid, and solid discharge streams.

Figure 1 is a schematic of the site H boiler and particulate control system. It illustrates a typical sampling and analysis protocol used in most of the test programs. For cofired systems such as the one shown in Figure 1, composite samples of both the waste fuel (location A) and primary fuel (location B) were obtained during each test performed. Waste fuel samples, not obtained during the baseline tests, were typically analyzed for concentrations of known POHC's, identification of other volatile and semivolatile organics, and ultimate analysis. As discussed in Section 2, waste fuels available at several test sites (E through K) were spiked with chlorinated organics (typically carbon tetrachloride, chlorobenzene, and trichloroethylene) to broaden the range of available POHC destruction data.

The primary fuel, whether liquid (typically no. 6 oil) or solid (wood waste or coal), was sampled primarily for proximate and ultimate analysis for quantification of C, H, N, Cl^-, O, ash, moisture, and heating value. However, for some sites the analysis was expanded to include inorganic elements, primarily priority pollutant metals (Sb, As, Be, Cd, Cr, Cu, Pb, Mu, Hg, Ni, Se, Ag, Tl, and Zn). Inorganic trace element data are not discussed in this report but are available in the individual test reports for sites H, I, and K (References 5, 6, and 7).

Flue gas emissions were measured for the most part at the stack, downstream of any pollutant scrubbing device. In the case of the site H boiler equipped with a regenerative air preheater and a cold-side electrostatic precipitator (ESP), criteria gaseous emissions were measured at both air heater inlet (location D) and stack (location F) due to flue gas dilution with combustion air across the air preheater. Throughout this report, criteria gaseous emissions refer to O_2, CO_2, CO, SO_2, NO_x and total unburned hydrocarbons (TUHC). These were measured in all cases with electronic analyzers operating on a continuous real-time basis.

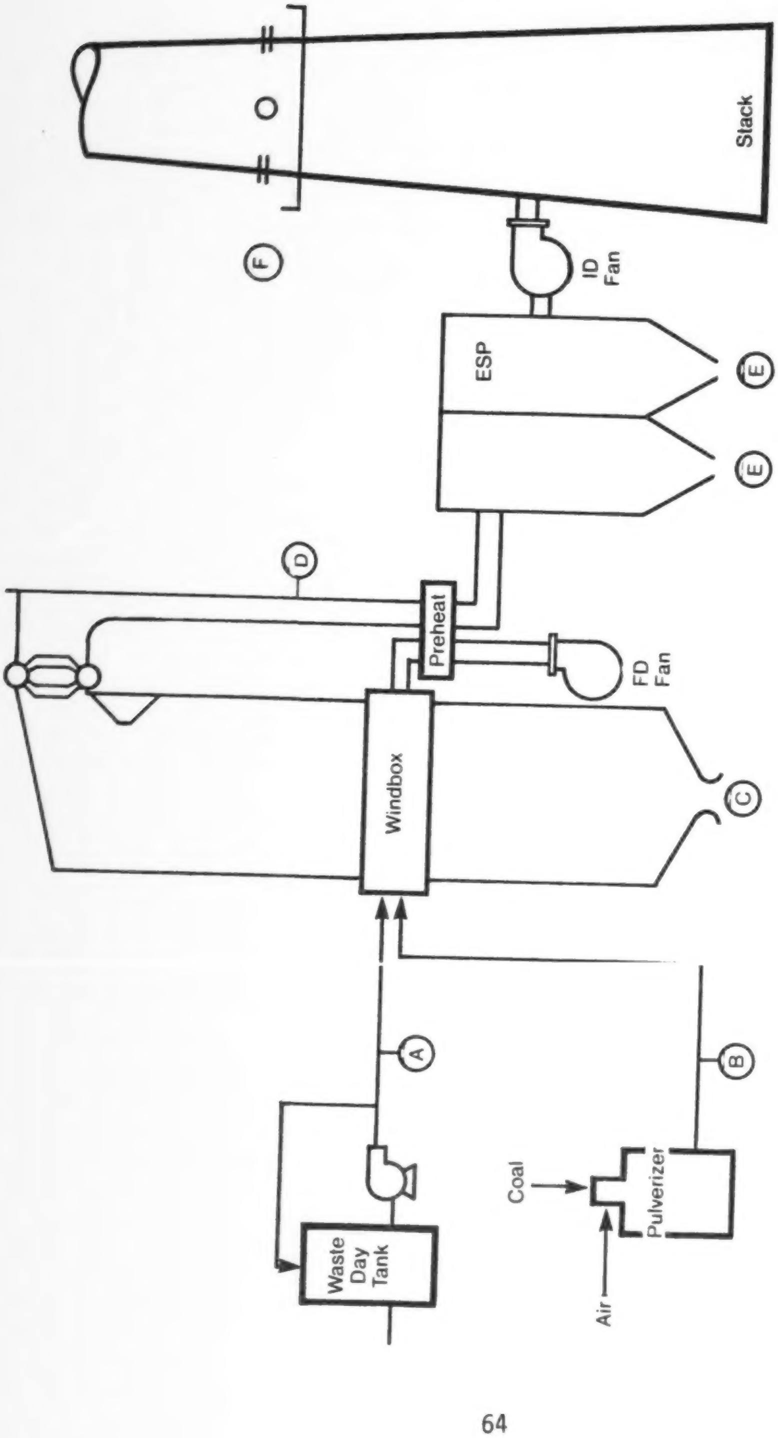

Waste Day Tank
Air
Coal
Pulverizer
A
B
Windbox
C
FD Fan
Preheat
D
ESP
E
E
ID Fan
F
Stack

Figure 1. Sampling protocol schematic -- site H.

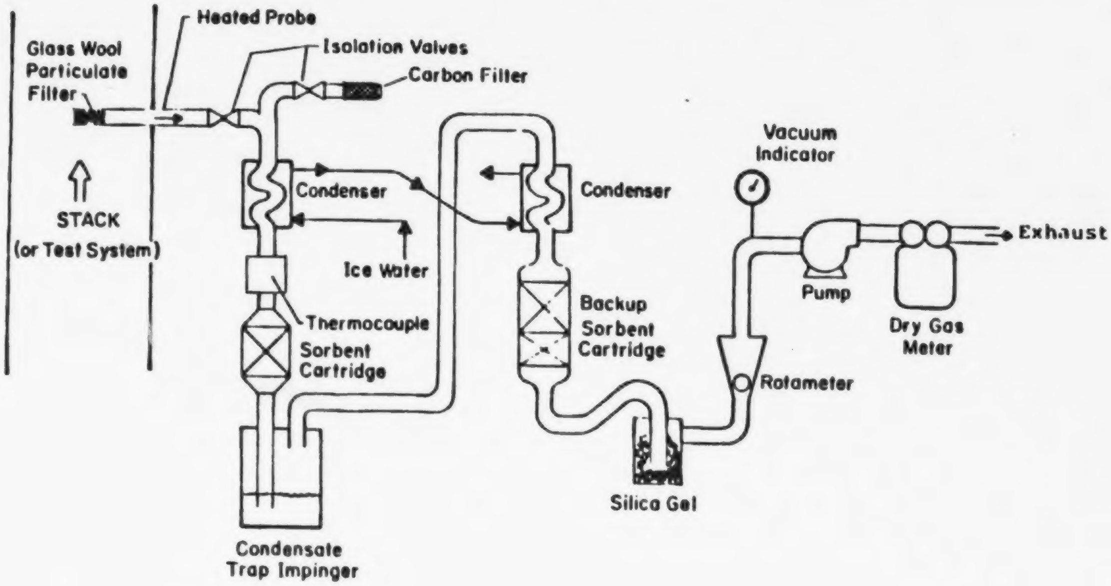
All organic emission measurements and other pollutant measurements were generally made at the stack. These measurements included:

- Volatile organics: POHC's and other priority pollutants (PIC's)
- Semivolatile organics: POHC's and other priority pollutants
  Particulate matter (inorganics)
  Chloride (HCl)
- Total chlorides (HCl): Primarily HCl
- Hydrocarbon speciation: C_1 to C_6 speciation

Volatile organics, those having boiling points less than 130°C (260°F) (e.g., chlorobenzene), were generally measured using the volatile organic sampling train (VOST), illustrated in Figure 2. However, due to the evolution of this sampling protocol which followed some initial test programs, several sites were not tested with this EPA-specified system. These are sites A, B, C, D and E. For sites A, B and C, a single heated Tenax sorbent trap was used which precluded efficient collection of volatile organics. For sites D and E, dual cold Tenax sorbent traps were used with impinger systems for condensate collection. Although significantly more effective, these systems showed greater collection of volatile organics in the impinger condensate which was also analyzed and included in the emission data calculation. The EPA VOST was used for all other test sites. The analysis of volatile organics was generally accomplished by thermal desorption of traps into a gas chromatograph (GC) with mass spectrometry (MS), electron capture detection (ECD), Hall detection, or flame ionization detection (FID). Selection of the detection methodology was generally based on analysis of specific compounds or classes of compounds (e.g., halogenated organics) or on analysis of a broad range of organics (e.g., priority pollutants).

Semivolatile organics were collected in all cases using a modified EPA Method 5 (MM5) sampling train, illustrated in Figure 3, with minor differences from site to site. Generally, organics were extracted from all portions of the train including the XAD-2 organic sorbent, filter media and impinger solution. Occasionally the impinger section was modified to include sorbents for collection of HCl (site I). Analysis of extracted organics was accomplished by GC/MS, GC/ECD or GC/FID, again depending on the selected organic groups sought in the analysis. The procedures generally conformed to EPA Method 625.

For sites D, E, F, G, H, J and K, a modified version of the EPA Method 6 equipment train was used to collect gas samples for total chloride (HCl) analysis. Laboratory analysis was generally accomplished using the colorimetric technique. Volatile hydrocarbon speciation by boiling point ranges, C_1 to C_6, was performed on flue gas samples collected at sites D, E, F, G and H. This was often done in place of continuously monitoring TUHC and also to provide speciation of hydrocarbon groups distinguished by boiling point ranges.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Isolation Valves
Carbon Filter
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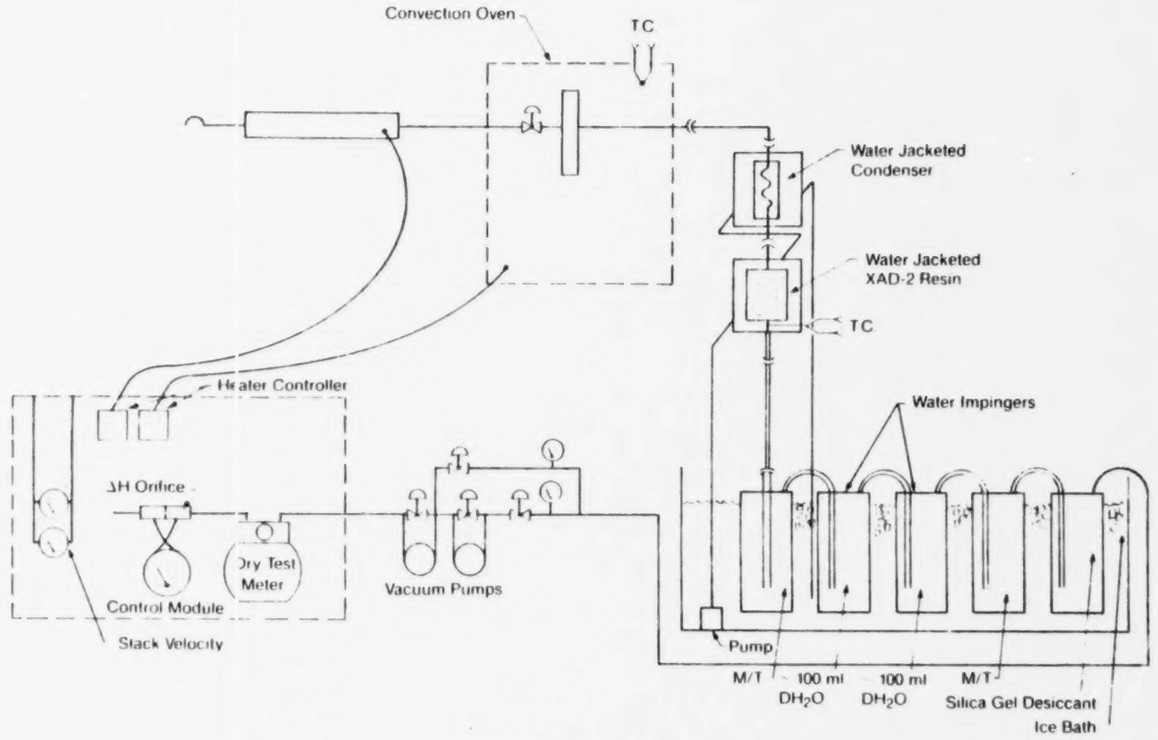
Condenser
Ice Water
Thermocouple
Sorbent Cartridge
Condensate Trap Impinger
Condenser
Backup Sorbent Cartridge
Silica Gel
Vacuum Indicator
Rotameter
Pump
Dry Gas Meter
Exhaust

Figure 2. VOST schematic (reference 8).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TC
Water Jacketed Condenser
Water Jacketed XAD-2 Resin
TC
Heater Controller
Water Impingers
ΔH Orifice
Dry Test Meter
Control Module
Stack Velocity
Vacuum Pumps
Pump
M/T
100 ml DH2O
100 ml DH2O
M/T
Silica Gel Desiccant
Ice Bath

Figure 3. Modified EPA Method 5 schematic.

Liquid and solid discharge streams were also sampled and analyzed at sites equipped with air pollution control devices. At site H (Figure 1) both bottom ash and ESP collected flyash were sampled and analyzed for semivolatile and nonvolatile organics as well as inorganic trace elements. These samples were generally composited over the duration of each test as in the case of fuel samples. The objective of these sample analyses was to provide organic and inorganic partitioning data for solid streams versus gaseous (flue gas) streams. Organics detected in either liquid or solid discharge streams are not accounted for in the calculation of POHC destruction, which by definition is based only on the flue gas organic emission rate. Other test sites where liquid or solid discharge streams were sampled were site A (multicyclone and bottom ash) and site G (scrubbers inlet makeup water and outlet discharges). Organic concentrations and emission rates due to these streams are discussed separately from measured flue gas emissions in Section 4.

Table 39 summarizes the sampling and analysis protocol used at each test site. Detailed discussions on site-specific protocols including equipment and related QA/QC activities are presented in Volume II (Data Supplement) of this report.

TABLE 39. SAMPLING AND ANALYSIS PROTOCOLS

Site	Baseline	Cofire	Fuels sampling and analysis protocols	Flue Gas Sampling and Analysis Protocols					Solid and liquid discharge streams sampling and analysis protocols
				Sample location	Continuous monitors	VOST[a]	Modified EPA Method 5 (MM5)	Other wet sampling systems	
A	-	4	• Creosote sludge: POHC's, other semivolatile organics and ultimate analysis • Wood and creosote mixture: ultimate analysis	Multiclone outlet (stack)	O_2, CO_2, CO, NO_x and TUHC	NA	• Semivolatile POHC's and EPA priority pollutants • Particulate		• Multiclone flyash: semivolatile and nonvolatile priority pollutants
B	1	3	• Alkyd resin wastewater: POHC's, other priority organics and ultimate analysis	Stack	O_2, CO_2, CO, NO_x and TUHC	NA	• Semivolatile POHC's and EPA priority pollutants • Particulate		
C	1	3	• Phenolic cumene waste: POHC's, other priority organics and ultimate analysis	Stack	O_2, CO_2, CO, NO_x and TUHC	NA	• Semivolatile POHC's and EPA priority pollutants • Particulate		
D	1	6	• Two separate chlorinated waste fuels: POHC's other priority organics and ultimate analysis	Stack	O_2, CO_2, CO, NO_x and SO_2	• Volatile organics: primarily POHC's	• Semivolatile POHC's and EPA priority pollutants • Particulate	• Modified EPA Method 6: total chloride • C_1-C_6 by FID	
E	1	8	• Three separate chlorinated and nonchlorinated waste fuels: POHC's, other semivolatile organics, and ultimate analysis • Oil: ultimate analysis	Stack	O_2, CO_2, CO, NO_x and SO_2	• Volatile organics: POHC's and other EPA priority and nonpriority pollutants	• Semivolatile POHC's and EPA priority pollutants • Particulate	• Modified EPA Method 6: total chloride • C_1-C_6 by FID	
F	1	3	• Chlorinated purge paint thinner: volatile POHC's and ultimate analysis	Stack	O_2, CO_2, CO, NO_x and TUHC	• Volatile organics: POHC's and other volatile priority pollutants	• Semivolatile POHC's and EPA priority pollutants • Particulate	• Modified EPA Method 6: total chloride • C_1-C_6 by FID	
G	-	3	• Highly chlorinated fuel: volatile and semivolatile POHC's, other major semivolatile organic and ultimate analysis	Recovery scrubber and HCl scrubber outlet (stack)	O_2, CO_2, CO, NO_x and TUHC	• Volatile organics: POHC's and other volatile priority pollutants	• Semivolatile POHC's and EPA priority pollutants • Particulate	• Modified EPA Method 6: total chloride • C_1-C_6 by FID	
H	1	3	• Chlorinated methyl acetate: volatile POHC's • Coal: ultimate analysis and metals	ESP outlet (stack)	O_2, CO_2, CO, NO_x, SO_2 and TUHC	• Volatile organics: POHC's and other volatile priority pollutants	• Semivolatile POHC's and EPA priority pollutants • Particulate • Metals	• Modified EPA Method 6: total chloride • C_1-C_6 by FID	• Inlet and outlet of scrubbers: volatile priority pollutants and total chlorides
I	2	2	• Chlorinated nitrobenzene, aniline and benzene mixture: volatile and semivolatile POHC's, metals, and ultimate analysis	Stack	O_2, CO_2, CO, NO_x and TUHC	• Volatile organics: POHC's and other volatile priority pollutants	• Semivolatile POHC's EPA priority pollutants, total chloride and selected metals	• Semivolatile POHC's by FID	• ESP flyash: semivolatile priority pollutants, wastes • Bottom ash: semivolatile priority pollutants, metals
J	-	6	• Chlorinated toluene mixture: volatile POHC's	Stack	O_2, CO_2, CO, NO_x and TUHC	• Volatile POHC's[b]	• Semivolatile POHC's	• Modified EPA Method 6: total chloride	
K	-	2	• Heavy and light oil: ultimate analysis, metals • Chlorinated oil: volatile POHC's and semivolatile organics	Stack	O_2, CO_2, CO, NO_x, SO_2 and TUHC	• Volatile POHC's	• Semivolatile POHC's, other semivolatile organics, metals	• EPA Method 6: total chloride	

[a] Tenax sorbent sampling at sites A, B and C was performed with a rudimentry sampling system and prior to the development of the VOST protocol. For sites D and E a developmental VOST was used. All other test sites used the EPA approved VOST.

[b] EPA Method 23 (bag samples) was also used at this site to compare results obtained with VOST. EPA Method 23 results are not discussed in this report.

SECTION 4

EMISSIONS RESULTS

Section 2 indicated that, for the most part, test boilers were operated under normal conditions of excess combustion air, heat input rates, ratio of waste to primary fuel, total chlorine input, etc., dictated by test site operating practices. Furthermore, tests were performed under relatively steady boiler operation to minimize possible impacts of sudden transients on emissions. Few tests, however, were performed under modified operation such as high and low excess combustion air and high and low boiler loads. The intent of these tests was to investigate the effect of minor operational changes on POHC destruction and overall organic emission rate. Also during some tests, combustion instability resulted in periods of high CO and smoke emissions. Although emission testing was normally halted during these periods, some impact of these unsteady operating conditions is evident from the emission results.

Table 40 summarizes the boiler test conditions investigated. Test numbers listed in the table are used throughout this section to relate emission results with boiler operating test conditions detailed in Section 2. Overall, 42 waste fuel firing tests were performed. With the exception of sites G and J, all tests were performed with the boiler burning a conventional fuel supplemented with a waste fuel containing POHC's. With the exception of sites B and C, all boilers were tested with heat loads within the typical operating load range for industrial boilers, generally corresponding to about 40 to 80 percent of design capacity. Test loads at sites B and C were about 25 percent of capacity. The following sections summarize the results obtained from measurements of criteria emissions by continuous monitors, C_1 to C_6 hydrocarbons, particulate, and HCl emissions. Results on POHC's, PIC's and other organic components are presented in Sections 4.2 and 4.3, respectively.

4.1 CRITERIA EMISSIONS

The flue gas at the stack was sampled continuously for criteria gaseous emissions (O_2, CO_2, CO, NO_x, and TUHC) at sites A through K. The TUHC measurement devices were not always operational, so these data are missing at some sites. CO, NO_x, and TUHC values are corrected to a 3 percent O_2 basis. In addition, gas sampling trains were used for measurements of gaseous hydrocarbons, speciated by boiling points (C_1 to C_6) (at sites D, E and G), total solid particulate matter, and hydrochloric acid emissions.

TABLE 40. SUMMARY OF TESTS[a]

			Volumetric heat release rates, MW/m^3 (10^3 Btu/hr-ft^3)										
			<0.10-0.41 (<10-40)[c]				0.42-1.0 (41 to 100)[d]				>1.0 (>100)[e]		
Site	Boiler type[b]	Primary fuel	<0.10 (<10)	0.11-0.21 (11-20)	0.22-0.31 (21-32)	0.32-0.41 (31-40)	0.42-0.52 (41-50)	0.63-0.72 (61-70)	0.73-0.82 (71-80)	0.83-0.93 (81-90)	1.05-1.14 (101-110)	145-166 (140-160)	>166 (>160)
A	WT	Wood			1,2,3,4								
B	FT	Natural gas											
C	WT	Natural gas	2,3,4						2,3,4				
D	WT	Oil			5,6,7	2,3,4							
E	WT	Oil/natural gas				6,9	2,3,4,5,8		7				
F	WT	Oil		2,3,4									
G	FT	--											
H	WT	Pulverized coal		2,3,4					1,2,3				
I	WT	Natural gas					2[f],4						
J	FT	--											
K	WT	Oil			2			5[g]		1,3		4[g]	2,6

[a] All tests performed at nominal combustion excess air levels unless otherwise indicated.

[b] WT -- watertube, FT -- firetube.

[c] This range corresponds to watertube (WT) boilers burning solid fuels at or near full load and WT boilers burning gas or liquid fuels at low loads (<50 percent of capacity).

[d] This range corresponds to WT boilers burning gas or liquid fuels at base loads (up to 80 percent of capacity) and FT boilers burning gas or liquid fuels at low loads ($\leq$60 percent capacity).

[e] This range corresponds to FT boilers burning gas and liquid fuels at or near operating capacity.

[f] Staged combustion air test.

[g] High excess air tests.

4.1.1 Gaseous Emissions

Table 41 summarizes gaseous emissions measured at the stack using continuous gas analyzers for all eleven sites A through K. The data show a wide range in the gaseous emissions from site to site. Test average CO corrected to 3 percent O_2 ranged from 18 for site C to over 4,000 ppm for site A; NO_x emissions ranged from about 40 ppm for site B to over 1,100 ppm for site I; and TUHC emissions, when available, ranged from undetected to 160 ppm. The following paragraphs summarize site-specific characteristics of these emissions.

Site A

At site A, the emission trends were erratic. This is typical of small industrial wood waste-fired boilers which are generally operated with excessively high volumes of combustion air to compensate for poor fuel/air mixing of fuel bed combustion and nonhomogenous physical and chemical properties of wood wastes. CO values typically ranged from about 300 to greater than 1,000 ppm as measured. CO instrument capability was limited to 1,000 ppm detection. High emissions of CO during these tests are attributed to the high excess air levels which led to quenching of combustion products, short furnace residence times, and rapid combustion gas cooling downstream of the bridgewall. Also the near batch feed of this boiler design contributed to fluctuation in O_2, CO_2, and CO emissions. Total hydrocarbons followed CO emission trends. O_2 levels were usually in the range of 9 to 11 percent, dropping down to 4.5 percent probably during surges in wood fuel feedrates. O_2 levels were highest at low loads due to reduced fuel input.

Site B

The site B boiler operated with about 30 percent excess air for all four tests. Slightly higher combustion air was utilized during cofire tests. The trend appears to be toward lower NO_x and CO and higher TUHC concentrations during the cofiring tests relative to baseline. The large variation in waste composition (particularly water content) is probably responsible for variations in emissions over the three cofiring runs. Test 4 was plagued by wastewater feed pump problems. During this test in particular, the CO level rose to 260 ppm and the NO_x dropped to 30 ppm (corrected to 3 percent O_2) in contrast to average values of 45 ppm CO and 40 ppm NO_x when there was no apparent feed water problem. This was attributed to surges in wastewater feed which quenched the gas flame resulting in CO and hydrocarbon spikes and lower NO_x.

Site C

This boiler was operated at very low loads. The low load operation in each test resulted in high excess air levels in the range of 80 to 95 percent, corresponding to O_2 levels in the range of about 10 to 11 percent. High combustion air volumes are often required to promote good air fuel mixing and maintain flame stability at low boiler loads. Furthermore, air flow to burner out of service was not shut off as with the

TABLE 41. CRITERIA FLUE GAS EMISSIONS

		As measured, dry basis		Corrected to 3 percent O_2, dry basis		
Test	Fuel(s)	O_2 (percent)	CO_2 (percent)	CO (ppm)	NO_x (ppm)	TUHC (ppm)
Site A						
1	Woodchips, sawdust, bark and creosote waste	7.7-16.5 (10.4)[a]	12.5-4.8 (10.1)	342->4,010 (1,070)[b]	137-223 (163)	0-163 (17)
2		6.2-16.7 (10.4)	14.8-4.4 (10.1)	274->4,200 (1,200)[b]	137-437 (210)	NA
3		6.2-15.5 (10.4)	13.4-5.6 (9.5)	223->3,260 (977)[b]	137-201 (171)	NA
4		5.0-13.2 (10.5)	15.4-6.6 (9.7)	257->2,570 (900)[b]	150-283 (180)	NA
Site B						
1	Natural gas	4.5-5.7 (4.9)	9.2-9.8 (9.5)	42-58 (52)	60-72 (65)	47-125 (70)
2	Natural gas and alkyd wastewater	4.2-5.5 (5.3)	9.1-9.9 (9.4)	38-58 (47)	34-63 (44)	59-166 (89)
3		5.5-6.0 (5.7)	8.8-10.4 (9.1)	36-54 (47)	61-68 (65)	59-173 (85)
4		3.8-6.4 (5.0)	9.0-12.4 (10.2)	23-258 (88)	32-62 (40)	8-81 (47)
Site C						
1	Natural gas	9.4-10.7 (10.0)	6.0-7.6 (6.5)	16-25 (20)	80-116 (96)	0
2	Natural gas and phenolic waste	7.8-10.3 (9.7)	6.6-8.7 (7.6)	13-24 (21)	52-84 (61)	0
3		8.3-11.1 (10.5)	6.2-8.0 (7.3)	12-21 (20)	60-103 (74)	0-7 (0)
4		8.5-11.3 (10.7)	6.4-8.5 (7.1)	18 (18)	61-89 (66)	0-5 (0)
Site D						
1	No. 6 oil	5.3-5.9 (5.4)	11.1-12.6 (11.8)	40-104 (75)	229-257 (240)	NA
2	No. 6 oil and solvent stream no. 3	4.9-5.4 (5.1)	11.6-12.8 (12.2)	81-161 (118)	232-275 (250)	NA
3		4.3-6.4 (5.2)	11.8-13.9 (12.9)	58-101 (88)	197-283 (242)	NA
4		4.6-5.7 (5.3)	11.8-15.0 (12.9)	82-128 (107)	200-246 (231)	NA
5	No. 6 oil and solvent stream no. 6	5.8-6.4 (6.0)	11.6-12.6 (12.2)	74-143 (107)	195-207 (203)	NA
6		5.2-6.8 (6.2)	10.7-12.6 (11.8)	62-160 (100)	185-211 (202)	NA
7		5.7-6.1 (5.9)	11.8-12.4 (12.1)	107-171 (127)	188-198 (193)	NA

(continued)

[a] Number in parentheses indicate averages of recorded data. Ranges indicate minimum and maximum recorded values.
[b] Average does not account for emissions exceeding the instrument measurement limit.
[c] Questionable emission measurements due to instrument malfunction.

NA -- data are not available.

TABLE 41. (continued)

		As measured, dry basis		Corrected to 3 percent O_2, dry basis		
Test	Fuel(s)	O_2 (percent)	CO_2 (percent)	CO (ppm)	NO_x (ppm)	TUHC (ppm)
Site E						
1	No. 6 oil	3.4-4.6 (3.8)	11.8-3.5 (12.3)	64-125 (87)	259-299 (278)	NA
2	No. 6 oil and TSB	5.3-6.9 (5.5)	9.5-12.8 (11.6)	81-129 (97)	334-402 (378)	NA
3	No. 6 oil and chlorinated TSB	5.3-7.5 (6.4)	9.2-12.8 (11.2)	93-339 (135)	360-530 (431)	NA
4		6.0-8.0 (7.0)	9.0-11.6 (10.3)	86-182 (129)	371-464 (439)	NA
5		6.0-8.0 (7.2)	9.0-11.6 (10.2)	115-167 (138)	380-454 (413)	NA
6		5.2-7.4 (6.3)	10.0-12.8 (11.7)	89-178 (115)	393-495 (446)	NA
7		6.5-8.5 (7.4)	9.3-11.0 (10.4)	91-203 (134)	316-396 (359)	NA
8	Natural gas and chlorinated TSB	5.3-6.8 (6.2)	9.0-10.4 (9.6)	50-132 (83)	423-548 (492)	NA
9	Natural gas and toluene/MMA mix	6.4-8.5 (7.4)	7.8-10.4 (8.6)	64-198 (106)	144-225 (164)	NA
Site F						
1	Oil	7.1-9.5 (8.6)	7.8-10.1 (9.0)	0-230 (135)	291-381 (328)	0-10.5 (4.0)
2	Oil and spiked thinner	7.0-9.5 (8.1)	8.1-9.6 (8.7)	11-206 (139)	246-329 (275)	0-4.2 (1.48)
3		7.3-9.9 (8.5)	7.1-10.3 (8.9)	18-219 (109)[c]	263-335 (299)	0-10.8 (0.34)
4		7.2-11.3 (8.5)	6.7-10.4 (9.1	NA	185-280 (243)	NA
Site G						
1	Chlorinated hydrocarbons spiked with carbon tetrachloride	8.3-9.0 (8.7)	8.4-10.2 (9.5)	146-205 (170)	63-72 (67)	0-1.5 (0.7)
2		8.5-8.7 (8.6)	8.9-10.2 (9.5)	123-174 (155)	65-71 (67)	0.3-1.6 (0.6)
3		8.2-9.4 (8.7)	8.4-9.9 (9.3)	124-160 (146)	70-79 (74)	0-0.7 (0.3)

(continued)

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[a] Number in parentheses indicate averages of recorded data. Ranges indicate minimum and maximum recorded values.

[b] Average does not account for emissions exceeding the instrument measurement limit.

[c] Questionable emission measurements due to instrument malfunction.

NA -- data are not available.

TABLE 41. (concluded)

		As measured, dry basis		Corrected to 3 percent O_2, dry basis		
Test	Fuel(s)	O_2 (percent)	CO_2 (percent)	CO (ppm)	NO_x (ppm)	TUHC (ppm)
Site H						
1	Pulverized coal	6.1-6.7 (6.4)	11.0-12.9 (11.7)	159-234 (201)	453-481 (466)	0-4.5 (2.6)
2	Pulverized coal and spiked methyl acetate	5.9-6.5 (6.3)	11.4-12.8 (12.1)	136-202 (157)	373-428 (394)	0-4.5 (1.0)
3		5.7-6.1 (6.0)	12.5-13.6 (13.2)	115-156 (144)	369-423 (393)	0-2.4 (0.5)
4		5.7-11.9 (6.5)	8.4-13.5 (12.0)	107-171 (142)	349-736 (427)	<0.5
Site I						
1	Natural gas	1.51-1.82 (1.7)	10.17-12.18 (11.0)	457-1,220 (750)	54-7 (64)	5-10 (7.9)
2	Natural gas and spiked aniline/nitrobenzene waste	2.38-2.70 (2.6)	10.19-10.70 (10.4)	61-231 (175)	371-444 (410)	5-7 (6.3)
3	Natural gas	2.30-2.45 (2.4)	9.79-10.28 (10.1)	34-70 (46)	72-81 (78)	4-6 (5.3)
4	Natural gas and spiked aniline/nitrobenzene waste	2.46-2.70 (2.6)	10.57-10.61 (10.6)	21-110 (63)	1,056-1,175 (1,125)	5-6 (5.2)
Site J						
1	Natural gas and waste fuel blend 1	5.9	12.2	129	203	2
2	Natural gas and waste fuel blend 1	4.0	14.2	135	87	NA
3	Natural gas and waste fuel blend 2	5.6	12.0	12	185	NA
4	Natural gas and waste fuel blend 1	6.3	11.7	108	92	NA
5	Natural gas and waste fuel blend 1	7.6	10.5	120	175	NA
6	Natural gas and waste fuel blend 2	3.2	14.2	20	85	NA
Site K						
1	No. 6 heavy oil	3.7-3.8 (3.8)	11.1-12.2 (11.5)	84-126 (102)	249-293 (278)	NA
2	Heavy oil and spiked light oil	3.8-4.3 (4.0)	10.5-11.7 (11.0)	91-158 (114)	150-158 (154)	NA

[a] Number in parentheses indicate averages of recorded data. Ranges indicate minimum and maximum recorded values.
[b] Average does not account for emissions exceeding the instrument measurement limit.
[c] Questionable emission measurements due to instrument malfunction.

NA -- data are not available.

case of natural gas. CO emissions (which were generally low, in the 20 to 30 ppm range) did not vary significantly from baseline to cofire tests. CO peaks greater than 25 percent of the average CO were never observed. Average NO_x emissions during the baseline test were 60 ppm as measured or 96 ppm corrected to 3 percent O_2 in the flue gas. These emissions, which are mostly attributable to thermal NO formation (bonding of N and O in the combustion air at elevated temperature), are comparable to other industrial gas-fired boilers operating at low load condition.

Combustion of the phenolic waste containing measurable amounts of nitrogen was anticipated to lead to a net increase in total NO_x emissions during the cofiring tests. However, since a net decrease in NO_x emissions was measured instead, the contribution of nitrogen in the phenolic waste to total NO_x was apparently insignificant. This is not unlikely since the form of fuel nitrogen and the combustion environment play much greater roles in fuel NO_x formation than the actual quantity of total nitrogen measured in the fuel. The net decrease in NO_x emissions during cofiring may be attributed to a lower furnace temperature caused by higher radiative properties of the phenolic waste and slightly lower boiler loads compared to the baseline test.

Site D

Average furnace O_2 concentrations were maintained relatively constant throughout each test, only registering a slight increase for the lower boiler load tests 5, 6, and 7. Slight increases in excess combustion air was implementeed to maintain smoke-free boiler operation especially following test 2 which was characterized by several smoke emission episodes and general flame instability.

Average CO emissions during the baseline test were lower than any of the cofired tests by about 10 to 40 ppm. This is indicative of the generally more stable firing condition during the baseline test. NO_x emissions during tests 2, 3, and 4 (cofiring no. 6 oil with solvent stream no. 3) were about the same as those of the baseline tests. The slight decrease in NO_x during test 3 and 4 from levels of 240 ppm of the baseline and 250 ppm of test 2 to about 230 ppm of test 4 was probably due to the steady increase in methanol concentration of the waste fuel. Methanol combustion produces a cooler flame resulting in lower thermal NO formation. Lower NO_x emissions during tests 5, 6, and 7 were probably the result of the lower firing rate of the boiler during these tests. The NO_x levels during tests 5, 6 and 7 were also quite steady throughout the test.

Boiler upsets affected the emission results for several site D tests. Primarily during cofire tests 2 and 3 there were frequent CO peaks as well as occasional unsteady waste flows.

Site E

Baseline O_2 measured at the stack was 3.8 percent, which was significantly lower than any of the cofiring tests. This indicates that stable and generally smoke-free operation during waste fuel combustion required increased amounts of excess air. CO emissions corrected to 3 percent O_2 averaged 87 ppm during the baseline test. Generally there was an increase in CO emissions during each of the cofiring tests with the exception of test 8. This is especially noticeable during tests 3 to 7 when fired fuels consisted of a mixture of no. 6 oil and chlorinated TSB. The high range in CO emissions during test 3 reflects several smoke emission episodes that occurred during this test.

NO_x emissions were lowest during tests 1 and 9. Baseline NO_x averaged 278 ppm at 3 percent O_2 when burning no. 6 oil only, while NO_x during test 9 averaged only 164 ppm at 3 percent O_2 when burning the toluene/MMA mix with natural gas. Lowest NO_x emissions during test 9 are attributed to a combination of natural gas firing, lower boiler load (lower surface heat release rate), and low nitrogen content of the toluene/MMA mix compared to TSB fuel.

Site F

Baseline O_2 levels at site F were slightly higher than the cofire average of 8.4 percent. No significant difference in average CO levels was observed between baseline and cofire test 2. However, burner combustion instability experienced throughout these tests resulted in several periods of high CO peaks and smoke emissions. The CO values for tests 3 and 4 are unreliable due to instrument malfunction.

NO_x emissions dropped during the cofiring tests. NO_x, corrected to 3 percent O_2, averaged 328 ppm during the baseline test, while the cofiring tests had average NO_x emissions of 275, 299, and 243 ppm, respectively. The variation in NO_x emissions is counter to the weighted average nitrogen content of the fuel. Thus, the highest NO_x emissions (327 ppm at 3 percent O_2) were generated during the baseline test, which had the lowest fuel nitrogen content (0.41 percent), and the lowest NO_x emissions (275 ppm at 3 percent O_2) were generated during the cofiring test with the highest weighted average fuel nitrogen content (0.46 percent). Heterocyclic nitrogen compounds are used in the pigments of the paint purged by the thinner from the paint lines, although not in quantities large enough to account for the levels detected in the waste fuels. The ultimate analysis indicated that the nitrogen was probably not in a -3 oxidation state as is normally encountered in fuels.

Site G

Emissions were generally constant throughout each test and between tests. O_2 concentrations measured consistently above 8 percent, at times increasing above 9 percent. Since induced draft fan settings remained unchanged during the test program, this change in O_2 concentration reflects a combination of minor changes in boiler feed properties and ambient air temperature.

Emissions of CO ranged from about 120 to 200 ppm corrected to 3 percent O_2 at stack conditions. Generally, the higher CO emissions were recorded during test 1, 170 ppm average, decreasing during test 2 to 155 ppm average and further still to 146 ppm during test 3. Since boiler operating conditions remained relatively unchanged throughout the test program, the steadily decreasing CO emissions from test 1 to test 3 may be attributed principally to fuel properties and slight increases in excess air. Also, the decreasing CO concentration in the flue gas coincided with decreases in atomizing air flowrate and boiler temperature profile. Lower atomizing air flowrates were the result of slightly higher burner gas pressures during tests 2 and 3 which, in turn, may have resulted in smaller feed droplet size distribution, more efficient combustion, and lower gas temperatures at the outlet of each boiler pass.

NO_x emissions averaged 67 ppm during tests 1 and 2 and 74 ppm at 3 percent stack O_2 during test 3. With the exception of a portion of the test 1 feed, the nitrogen content of the feed was essentially nil. This suggests that NO_x emissions were generally the result of thermal NO formation. These emission rates, which on a heat input basis correspond to about 35 ng/J, are similar to those of a firetube boiler burning natural gas.

Total unburned hydrocarbons were generally less than 1 ppm and tended to decrease throughout the test program in a way similar to CO emissions. This is consistent with the concept of slightly improved combustion efficiency during the last test.

Site H

Site H criteria gas emissions were generally constant throughout the test program. Excess O_2 ranged between 5.7 to 6.5 percent for most tests with the exception of test 4 (the last cofire test) where occasionally O_2 was measured in excess of 10 percent. It is not clear what caused these short-term excursions in excess air. CO emissions averaged 200 ppm corrected to 3 percent O_2, for the baseline test, typical of pulverized coal-fired boilers. Cofiring methyl acetate waste at 2 to 4 percent of the total heat input resulted in lower CO emissions in the range of 140 to 160 ppm corrected to 3 percent O_2. Also NO_x emission showed a decrease of 10 to 16 percent from baseline levels of 466 ppm at 3 percent O_2. Total unburned hydrocarbons were generally low in the 0 to 4.5 ppm range.

Site I

Test conditions at site I included emission evaluation during staged and unstaged combustion. Baseline tests 1 and 3 with natural gas combustion resulted in NO_x emissions in the range of 64 to 78 ppm at 3 percent O_2. CO emissions during staged combustion test 1 increased to 750 ppm. Some increase in TUHC was also recorded. Cofiring tests 2 and 4 showed a similar emission pattern. Unstaged combustion test 4 resulted in high NO_x emission (1,125 ppm at 3 percent O_2) mostly attributed to fuel NO from nitrobenzene and aniline organics. Combustion staging increased CO from 63 to 175 ppm also with some minor increase in TUHC.

Site J

The boiler at site J was operated under varied loads and excess air conditions. This is reflected in the O_2 concentrations which ranged from 3.2 to 7.6 percent. No baseline tests were performed. There was a substantial difference in CO levels for the combustion of fuel blend 1 and 2. Average CO levels for tests 3 and 6, (12 and 20 ppm, respectively) which fired fuel blend 2, were less than one fifth of the lowest average level for the other runs which fired fuel blend 1. Since changes in excess air levels between tests are insufficient to account for CO emission differences, these CO trends may be attributed to fuel blend characteristics.

Concentrations of NO_x ranged from 85 to 92 ppm for full load conditions (tests 2, 4, and 6) and 175 to 203 ppm for reduced load conditions (tests 1, 3, and 5). The trend of lower NO_x at half loads holds true for both fuel blends and several excess air levels.

Site K

Two tests were performed at site K with approximately constant excess O_2 (3.8 to 4.0 percent). The cofired test 2 resulted in slightly higher average CO emissions although the wider CO range indicates a much greater CO sensitivity during cofiring than during baseline combustion conditions. The NO_x emission reduction from 278 ppm of baseline to 154 ppm at 3 percent O_2 of cofiring is attributed primarily to the partial displacement of heavy oils with POHC spiked light oil.

4.1.2 C_1 to C_6 Hydrocarbons

Volatile gas phase hydrocarbons having boiling points in the nominal range of -160° to 100°C were measured at some sites by multiple analyses of the flue gas samples using onsite gas chromatography. The detection limit of this technique was generally 1.0 ppm corresponding to approximately 0.7 (C_1) to 3.5 (C_6) mg/dscm. Table 42 summarizes the results of these measurements for test sites D, E, and G. These data were developed only for these sites. Mostly higher boiling point hydrocarbons ($\geq C_5$) were detected at sites D and E. Conversely at site G, C_1 and C_3 hydrocarbons were almost exclusively detected.

Generally, an increase in gaseous C_1 to C_6 hydrocarbons were measured when converting boiler operation to hazardous waste cofire. This is evidenced by site D and E results. Also the level of hydrocarbon emissions does not indicate a dependence on type of primary of waste fuels used. However, generally higher C_1 to C_6 hydrocarbon emissions were measured during tests characterized by boiler transients, increases in stack opacity, and higher soot and smoke emission levels.

TABLE 42. C_1 TO C_6 HYDROCARBON EMISSIONS SUMMARY, ppm[a]

Site	Number of tests	Primary fuel	Waste fuel	Hydrocarbons, ppm as measured						Total
				C_1	C_2	C_3	C_4	C_5	C_6	C_1 to C_6
D	1	No. 6 oil	None						5	5
	3	No. 6 oil	Tetrachloroethylene in methanol waste	0-2 (1)	0	7-9 (8)	1-6 (2)	0-9 (3)	0-10 (6)	8-36 (20)
	3	No. 6 oil	Bis(2-chloroethyl)ether in toluene waste	0	0	0-10 (3)	0-2 (1)	6-35 (16)	6-9 (7)	6-56 (27)
E	1	No. 6 oil	None	0	1	2	1	28	6	37
	1	No. 6 oil	TSB with MMA polymers	0	0	0	1	57	83	142
	5	No. 6 oil	TSB spiked with carbon tetrachloride, chlorobenzene, and trichloroethylene	0	0	1-2 (1)	0-2 (1)	10-58 (32)	1-82 (31)	12-140 (65)
	1	Natural gas	TSB spiked with carbon tetrachloride, chlorobenzene, and trichloroethylene	0	1	2	3	63	37	104
	1	Natural gas	Toluene/MMA mixture	0	0	1	1	30	26	56
G	3	None	Chlorinated organics with carbon tetrachloride	4-10 (6)	0-2 (1)	4-5 (4)	0-1 (0)	0	0	7-16 (11)

[a] Ranges are based on test average emissions; number in parentheses is the average for all specified tests.

4.1.3 Particulate and HCl Emissions

Table 43 summarizes particulate and HCl emissions measured in the stack downstream of any air pollution control device. Particulate emissions at site A were controlled with a multiclone. Flyash collection efficiency of this control device was estimated to be about 50 percent. Particulate emissions during cofiring at site D were lower than those of the baseline emissions. This is due to the reduced contribution of inorganic ash in residual fuel oil during cofiring with methanol and toluene waste streams. The increase in total chlorine input during cofiring is evidenced by the increase in HCl emissions. Similar results were obtained at site E. Essentially no change in particulate emissions was measured during fuel oil cofired with third stage bottom (TSB) waste. General reductions in particulate emissions were measured for the other cofired tests with the exception of a high load test and other tests characterized by high smoke emissions. HCl emissions followed the chlorine input rate of waste fuels. Increases in both particulate and HCl were measured at site F. These results were due to increases in both ash and chlorine with cofired fuels.

At site G, flue gas HCl emissions were controlled by a halogen recovery scrubber and an HCl scrubber positioned in series. Stack HCl emission measurements indicated greater than 99 percent scrubbing efficiency. Other HCl results provided by test sites I through K showed emission increases due to cofiring with carbon tetrachloride, chlorobenzene, and trichloroethylene. Overall the measured chlorine in the output streams accounted for 80 to 130 percent of the total chlorine input from waste fuel combustion.

4.2 POHC EMISSIONS

This section summarizes emission results of principal organic hazardous constituents (POHC's) and other major organics present in combusted waste fuels at the eleven sites. The firing rates, along with the emission rates of these organics, were monitored to determine their destruction efficiency under several thermal environments and combustion conditions. The results of POHC DRE's are discussed in Section 5.

Table 44 summarizes the concentration of major organic compounds present in the waste fuels at each site. These compounds are categorized as RCRA Appendix VIII compounds (POHC's) and other major organics detected in the waste fuels. Compounds having concentrations less than 500 ppm were generally excluded from consideration. The focus of this section is the emissions of POHC's, primarily the volatile POHC's: carbon tetrachloride, trichlorethylene, chlorobenzene, toluene, benzene, tetrachloroethylene, methylmethacrylate, and 1,1,1-trichloroethane. The concentration of these organics in the feed generally ranged from about 0.1 percent (1,000 ppm) for benzene and chlorobenzene, to as high as 98 percent for toluene. A combination of carbon tetrachloride, trichloroethylene, and chlorobenzene was artificially added to waste fuels available at sites E through K to broaden the data base on POHC destruction and facilitate intrasource comparison.

TABLE 43. PARTICULATE AND HCl GAS EMISSIONS

Site	Number of tests	Primary fuel	Waste fuel	Total particulate emissions, g/s[a]	Chloride emissions as HCl, g/s[a]
A	4	Wood	Creosote waste	1.0	NA
D	1	No. 6 oil	None	6.3	0.21
	3	No. 6 oil	Tetrachloroethylene in methanol waste	1.1-1.8 (1.3)[b]	8.7-40.4 (24.2)
	3	No. 6 oil	Bis(2-chloroethyl) ether in toluene waste	0.24-0.27 (0.26)	4.0-5.7 (4.9)
E	1	No. 6 oil	None	0.30	0.05-0.27 (0.16)
	1	No. 6 oil	TSB with MMA polymers	0.32	0-0.19 (0.08)
	5	No. 6 oil	TSB spiked with carbon tetrachloride, chlorobenzene, trichloroethylene	0.25-1.0 (0.47)	6.5-12.3 (8.6)
	1	Natural gas	TSB spiked with carbon tetrachloride, chlorobenzene, trichloroethylene	0.09	7.9-9.3 (8.6)
	1	Natural gas	Toluene/MMA mixture	0.22	0.03-0.06 (0.05)
F	1	No. 6 oil	None	0.08	<0.01-0.77 (0.39)
	3	No. 6 oil	Waste paint solvents spiked with carbon tetrachloride, chlorobenzene, and trichloroethylene	0.36-0.44 (0.41)	0.91-5.0 (2.9)
G	3	None	Chlorinated organics spiked with carbon tetrachloride	0.21-1.8 (0.40)[c]	0.41-0.51 (0.47)[c]
I	2	Natural gas	None	NA	0.005-0.033 (0.015)
	2	Natural gas	Aniline, nitrobenzene waste spiked with carbon tetrachloride, chlorobenzene, and trichloroethylene	NA	2.3-2.9 (2.5)
J	6	None	Toluene, carbon tetrachloride, chlorobenzene, and trichloroethylene	NA	0.13-0.90 (0.51)
K	1	No. 6 oil	None	NA	0.034-0.036 (0.035)
	1	No. 6 oil	Light oil mixture spiked with carbon tetrachloride, chlorobenzene, and trichloroethylene	NA	2.6-2.8 (2.6)

[a] Numbers in parentheses indicate average of values obtained for each test.
[b] Multiclone system was used to trap ash.
[c] Halogen recovery and HCl scrubbers used to control Cl^- emissions.

NA -- not available.

TABLE 44. WASTE FEED CONCENTRATION OF MAJOR ORGANIC COMPOUNDS, 10^3 ppm by weight

Organic compound	Site[a]											Range
	A	B	C	D	E	F	G	H	I	J	K	
RCRA Appendix VIII compounds:												
Carbon tetrachloride	--	--	--	--	27-33	21-30	40-50	24-51	15-21	4.8-5.0	8.0-111	4.8-51
Trichloroethylene	--	--	--	--	24-31	7.8-61	--	--	14-20	10-20	8.0-9.0	8.1-61
Chlorobenzene	--	--	--	--	15-19	1.3-5.8	--	26-53	28-35	5.0-5.5	9.0	1.3-53
Tetrachloroethylene	--	--	--	45-300	--	--	--	--	--	--	--	45-300
Toluene	--	0.55	--	960	940	4.6-12	--	--	27-39	970-980	1.8-2.4	0.55-980
Benzene	--	--	--	--	--	--	--	--	14-21	--	1.0-1.5	1.0-18
Phenol	0.6-1.3	--	47-56	--	--	--	--	--	--	--	100-130	0.6-130
Pentachlorophenol	2.2-6.0	--	--	--	--	--	--	--	--	--	--	2.2-6.0
1,1,1-trichloroethane	--	--	--	--	--	--	--	20-41	--	--	--	20-41
2,4-dimethylphenol	0.3-1.3	--	--	--	--	--	--	--	--	--	--	0.3-1.3
Naphthalene	5.4-19	--	--	--	--	--	--	--	--	--	--	5.4-19
Methylmethacrylate	--	--	--	--	33-120	--	--	--	--	--	--	33-120
Bis(2-chloroethyl)ether	--	--	--	40-42	--	--	--	--	--	--	--	40-42
Epichlorohydrin	--	--	--	--	--	--	160-200	--	--	--	--	160-200
Bis(2-chloroisopropyl)ether	--	--	--	--	--	--	400-540	--	--	--	--	400-540
Nitrobenzene	--	--	--	--	--	--	--	--	830-860	--	--	830-860
Fluorene	4.4-7.6	--	--	--	--	--	--	--	--	--	--	4.4-7.6
Chrysene	0-2.4	--	--	--	--	--	--	--	--	--	--	0-2.4
Other organics:												
Anthracene	0.26-3.0	--	--	--	--	--	--	--	--	--	--	0.26-3.0
Aniline	--	--	--	--	--	--	--	--	18-28	--	--	18-28
Xylenes	--	0.27-2.7	--	--	--	--	--	--	--	--	42-55	0.27-55
Methylnaphthalene	1.3-2.2	--	--	--	--	--	--	--	--	--	--	1.3-2.2
Biphenyl	5.2-8.6	--	--	--	--	--	--	--	--	--	--	5.2-8.6
Pyrene	6.2-15	--	--	--	--	--	--	--	--	--	--	6.2-15
Phenanthrene	6.4-13	--	--	--	--	--	--	--	--	--	--	6.4-13
Methylpyrenes	0.88-1.9	--	--	--	--	--	--	--	--	--	--	0.88-1.9
C_3-alkylbenzene	--	--	38-100	--	--	--	--	--	--	--	--	38-100
Methylenebisphenol	--	--	0.83-6.7	--	--	--	--	--	--	--	--	0.83-6.7
Benzene acetaldehyde	--	--	4.7-6.4	--	--	--	--	--	--	--	--	4.7-6.4

[a] Primary fuels: site A -- wood chips; sites B, C, E -- natural gas; sites D, E, F, K -- no. 6 oil; site H -- pulverized coal.

Table 45 presents the concentrations of POHC's, both volatiles and semivolatiles, normalized based on the ratio of heat input of the waste fuel containing the POHC to the total heat input to the boiler. Test sites having the highest POHC concentrations on a heat input basis were sites C, D, E, G, J, and K. For sites G and J the fuel containing POHC contributed 100 percent of the heat input to the boiler. Boiling points and heat of combustion for specific compounds are also listed in Table 45. The boiling point provides an indication of a compound's volatility. The heat of combustion (HC) has been identified as a possible criteria for ranking the destructibility of compounds. That is, the lower the heat of combustion the more difficult the thermal destruction may be. However, this ranking criteria has been suggested as inappropriate in light of ongoing research in nonflame kinetics. This research has shown, for example, that tetrachloroethylene has a higher thermal stability than carbon tetrachloride. Generally, for chlorinated methanes higher thermal stability was found to correlate with increased chlorine substitution (Reference 3).

Organic emissions presented in this section are based on blank-corrected test sample concentrations. Although it is recognized that a relatively high degree of uncertainty exists due to minute concentrations sought in the sampling and analytical protocols, the data have not been corrected to reflect these uncertainties. Estimates of error bands in the data are discussed in Volume II (Data Supplement) of this report. The following section summarizes the background organic emission data obtained during primary fuel firing only (baseline). Emission data obtained during waste firing are discussed in Section 4.2.2.

4.2.1 Baseline Emissions

Table 46 summarizes baseline organic emissions for each test site. Each test for volatile organics generally consisted of triplicate measurements as in the case of cofiring tests. For these cases, which include all sites except A, B and C, the average measured emission is reported. Single measurements were made for sites A, B and C semivolatile organics. For all test sites except sites A, G, I and J one baseline was performed. No baseline tests were performed at sites A, G and J. At site I, two baseline tests were performed with unstaged and staged combustion conditions, respectively. As indicated in Section 3, site A wood fuel burned during an attempted baseline test was contaminated with creosote sludge and therefore the test was considered a cofire test. For site G, the fuel containing POHC's constituted 100 percent of the heat input to the boiler; while for site J, the primary fuel oil was spiked with POHC's, therefore becoming a hypothetical hazardous waste fuel. Dashes in Table 46 indicate concentrations below the detection limits for compounds specifically included in the analytical protocol.

A broad comparison of baseline organic emissions among test sites can be misleading unless some important aspects of the data are explained. For example, for sites B and C volatile organic emission data are essentially nonexistent because an appropriate sampling technique was not utilized. For sites H, I, and K, measurement of volatile organic emissions was limited to

TABLE 45. WASTE FUEL POHC CONCENTRATION NORMALIZED BY WASTE FUEL HEAT CONTRIBUTION, 10^3 ppm (WH/HT)

POHC[a]	Boiling point (°C)	HC (Kcal/g)	Site[b]										
			A	B	C	D	E	F	G	H	I	J	K
Volatile organics:													
Carbon tetrachloride	77	0.24	--	--	--	--	5.8-12	2.0-3.0	40-50	1.0-1.2	1.2-1.7	4.8-5.0	4.0-5.5
Trichloroethylene	87	1.74	--	--	--	--	6.0-12	0.78-6.1	--	--	1.1-1.6	10-20	4.0-4.5
Chlorobenzene	131	6.60	--	--	--	--	3.5-7.5	0.13-0.58	--	1.1-1.3	2.3-2.8	5.0-5.5	4.5
Tetrachloroethylene	121	1.20	--	--	--	8.0-90	--	--	--	--	--	--	--
Toluene	111	10.14	0.01	--	--	450	440	0.46-1.2	--	--	2.2-3.2	970-980	1.8-2.4
Benzene	80	10.03	--	--	--	--	--	--	--	--	1.1-1.7	--	1.0-1.5
1,1,1-trichloroethane	74	1.60	--	--	--	--	--	--	--	0.82-0.96	--	--	--
Methylmethacrylate	100	6.52	--	--	--	--	7.9-62	--	--	--	--	--	--
Semivolatile organics:													
Phenol	182	7.76	0.23-0.52	--	18-20	--	--	--	--	--	--	--	100-130
2,4-dimethylphenol	212	8.50	0.12-0.52	--	--	--	--	--	--	--	--	--	--
Naphthalene	218	9.60	2.2-7.6	--	--	--	--	--	--	--	--	--	--
Pentachlorophenol	310	2.09	0.88-2.4	--	--	--	--	--	--	--	--	--	--
Bis(2-chloroethyl)ether	104	3.38	--	--	--	18-20	--	--	--	--	--	--	--
Epichlorohydrin	116	5.20	--	--	--	--	--	--	160-200	--	--	--	--
Bis(2-chloroisopropyl)ether	188	4.93	--	--	--	--	--	--	--	--	--	--	--
Nitrobenzene	211	5.50	--	--	--	--	--	--	--	--	67-70	--	--
Fluorene	293	9.55	1.3-3.0	--	--	--	--	--	--	--	--	--	--
Chrysene			0-0.96	--	--	--	--	--	--	--	--	--	--

[a] RCRA Appendix VIII compounds.

[b] Concentration of organic compound normalized on the basis of the ratio of the amount of heat supplied by the waste fuel by the total heat to the boiler (waste fuel and primary fuel).

TABLE 46. BASELINE ORGANIC EMISSIONS (PRIMARY FUEL ONLY), µg/dscm

Compound	Site[a] B	C	D	E	F	H	I	K	Range for natural gas	Range for No. 6 oil
Volatile organics:										
Carbon tetrachloride[b]				--[c]	6.5[d]	--	1.1, 1.5[d]	3.1[d]	1.1-1.5	0-6.5
Trichloroethylene[b]			12	--	22[d]		0.6, 0.6[d]	--	0.6	0-22
Chlorobenzene[b]				24[d]	1.6[d]	0.26[d]	1.1, 5.0[d]	--	1.1-5.0	0-24
Tetrachloroethylene[b]			19[d]	64	--					0-64
Toluene[b]	6.7[d]		84[d]	480[d]	29[d]		4.9, 10[d]	5.2[d]	4.9-10	5.2-480
Benzene[b]			29		270		22, 46[d]	250[d]	22-46	29-270
1,1,1-trichloroethane[b]			37		16	--				16-37
Chloroform[b]					110					110
Chloromethane[b]					12					12
1,2-dichloroethane[b]					1.9					1.9
1,2-dichloropropane[b]					0.61					0.61
Chloroethane[b]					8.9					8.9
t-1,3-dichloropropane[b]					57					57
Ethylbenzene					4.6					4.6
Methylmethacrylate[b]				120[d]						120
Dichloromethane[b]					410					410
Semivolatile organics:										
Phenol[b]	--	2.5[d]	1.6	0.70	0.74				0-2.5	0.70-1.6
Xylenes	11	--	--	--	--				11	0
C_3-alkylbenzene	1.4	11	--	--	--				1.4-11	0
Methylenebisphenol	--	0.5	--		--				0-0.5	0
1,3-dichlorobenzene[b]	--	--	0.5	--	--				0	0-0.5
1,4-dichlorobenzene[b]	--	--	0.38	--	--				0	0-0.38
Naphthalene[b]	7.0	--	0.27	--	0.98				0-7.0	0.27-0.98
Phenanthrene	--	--	0.14	--	--				0	0.14
Ethylbenzaldehyde	7.1	--	4.7	5.6	7.4				0-7.1	4.7-7.4
Nitrobenzene							8.6, 9.5		9.1	
Aniline							4.4, 4.8		4.6	
Total organics detected[e]	33	14	190	690	960	0.26	43, 77	260	56-110	780-1,600
Primary fuel	Natural gas	Natural gas	No. 6 oil	No. 6 oil	No. 6 oil	Pulverized coal	Natural gas	No. 6 oil	Natural gas	No. 6 oil

[a] Baseline fuel for site A was contaminated.

[b] RCRA Appendix VIII compounds.

[c] Dashes indicate that compounds were specifically sought in the sample analysis but were either not detected or sample concentration was below blank concentration.

[d] POHC in the waste fuel cofired at the site.

[e] Total organics does not include additional semivolatile compounds such as phthalate and acids.

NA -- not sought in the analysis.

the POHC's present in the waste fuel. Furthermore, for sites I and K the measurement for semivolatile organics was also limited to the POHC's of the waste fuel. Therefore, the lack of emission data for a specific organic compound does not signify the absence of that compound in the sampled combustion products.

Combustion of fuel oil (sites D, E, F, and K) and coal (site H) produce a background level of chlorinated volatile and semivolatile organics and other polynuclear aromatics. Emissions of chlorinated organics include POHC's such as carbon tetrachloride, trichloroethylene, and chlorobenzene. These compounds were measured in the range of 0.6 to 5.0 μg/dscm with natural gas fuel and in the range of 0 to 24 ug/dscm with fuel oil. Toluene, benzene, and methylene chloride showed the highest concentration of any volatile or semivolatile compound. These high concentrations are in part attributed to field and laboratory contamination of samples. Similarly, the high concentration of methylmethacrylate (a POHC of the waste fuel for site E) is attributed for the most part to contamination.

Site F showed the largest array of volatile organic emission. This was due in part to improved sampling and analytical methodologies implemented at this site and in part to improper burner operational settings. As discussed in Section 3, the improper location of the burner nozzle in the burner throat resulted in nozzle coking, possible flame impingement, and frequent flameouts. The quantity of baseline organics for site F measured 960 μg/dscm, of which 67 percent is attributed to volatile chlorinated compounds. Although a likely contaminant, methylene chloride was not identified as such because the sample concentration exceeded both field and laboratory blanks.

From a mass balance viewpoint, both no. 6 oil and coal contained sufficient chlorine to account for all chlorinated organics measured during baseline testing. Chlorinated organic emissions measured during natural gas combustion may be indicative of the analytical "noise level" resulting from very low detection limits sought during these studies.

4.2.2 Cofire Emissions

Emissions measured during waste fuel firing were the basis for quantification of compound-specific DRE's for each test site. Principal volatile POHC's used for DRE determination were carbon tetrachloride, trichloroethylene, chlorobenzene, and toluene. These volatile compounds were POHC's for sites E through K. Additional volatile POHC's whose emissions were measured to determine DRE were 1,1,1-trichloroethane, benzene, tetrachloroethylene, and methylmethacrylate. Semivolatile POHC emissions of phenol, pentachlorophenol, 2,4-dimethylphenol, naphthalene, chrysene, and fluorene were determined primarily for sites A through D, although their emissions were sought in most other test sites through the analyses of semivolatile priority pollutants in the MM5 samples. Bis(2-chloroethyl)ether and epichlorohydrin were POHC's for site G. Nitrobenzene and aniline were POHC's for site I. This section focuses on the test-specific emission results for volatile and semivolatile POHC's indicated above. Emission of other major organic compounds (not listed in the RCRA Appendix VIII) are also reported.

Tables 47 through 50 summarize the test-specific emission results for the four most common volatile POHC's: carbon tetrachloride, trichloroethylene, chlorobenzene, and toluene. Emissions are presented according to load ranges: low, nominal, and high loads. Low loads generally refer to total boiler heat input less than 40 percent of boiler capacity. Nominal loads are heat inputs safe to the typical operating range of test boilers, 40 to 80 percent capacity; high loads refer to heat inputs at or near boiler design capacity. For each test, both the range in measured emissions and the arithmetic average emission are given. The following paragraphs highlight the main results and emission trench for each of the organic compounds.

Carbon Tetrachloride

Carbon tetrachloride emissions ranged from nondetected (designated as zero) to 800 μg/s. The average emission rates were below 40 μg/s for all test sites except site G, at 230 μg/s. This is not surprising because the waste fuel for site G accounted for all the fuel to the boiler. Moreoever, site G waste fuel contained over 50 percent by weight chlorine in the form of halocarbons. Since chlorine tends to delay combustion and reduce flame temperature, the large quantity of chlorine in the fuel may have been attributed to the high emissions at site G. On a flue gas concentration basis, carbon tetrachloride at site G was the highest, 26 to 400 μg/dscm, and site H was the lowest, at 0 to 1.7 μg/dscm. Some test-specific results and possible trends can be summarized as follows.

For site E, the low load test, no. 6 showed the highest average emission rate. This combined with the essentially unchanged firing rate of the waste fuel is likely to result in lower DRE. Peak carbon tetrachloride emissions for this site were measured during a portion of tests 3 and 7. Several burner upsets and smoke emission episodes during test 3 may have contributed to the high measurements. It should be reiterated that since an attempt was made to avoid flue gas sampling during periods of unstable combustion conditions, the emissions during test 3 may very likely not represent the worst emission rates. Overall, excluding nondetected levels, individual test measurements showed a variation of one order of magnitude. Test average emissions varied less than one order of magnitude between individual tests.

Site F results showed a trend of higher emission during the earlier tests. This trend coincided with more frequent unstable burner conditions during the earlier part of the test program. These burner upsets had resulted in frequent flameouts and test interruption. Most of the unstable burner conditions were resolved prior to test 4 which resulted in lowest carbon tetrachloride emissions.

Site G emissions of carbon tetrachloride were the highest of any test site as indicated above. These results are primarily due to the site high input rate of POHC's normalized on a total heat input basis. As indicated in

TABLE 47. CARBON TETRACHLORIDE (CCl_4) EMISSION RESULTS, μg/s[a]

Site	Boiler type	Primary fuel	Low load	Nominal load				High load			Range	Average
E	WT	No. 6 oil for tests 3, 4, 5, 6, and 7 Gas for test 8	66-81^{6} (74)	0-84^{3} (29)	1.3-27^{4} (18)	0-64^{5} (21)	5.2-20^{8} (12)	0-97^{7} (33)			0-97	29
F	WT	No. 6 oil		33-136^{2} (76)	24-27^{3} (26)	4.3-15^{4} (9.5)					4.3-136	37
G	FT	None		53-150^{1} (120)	120-800^{2} (460)	72-180^{3} (115)					53-800	230
H	WT	Pulverized coal						0-6.1^{2} (2.0)	0-13^{3} (4.3)	9.6-57^{4} (38)	0-57	15
I	WT	Natural gas		16-26^{2} (20)	25-34^{4} (29)						16-34	25
J	FT	None	0.6-2.3^{5} (1.2)	3.2-12^{1} (6.6)	0.4-4.4^{3} (2.3)			3.2-6.9^{2} (5.3)	0.3-1.3^{4} (0.8)	3.3-7.0^{6} (4.8)	0.3-12	3.5
K	WT	No. 6 oil		10-25^{2} (18)							10-25	18

[a] In order to convert emission rates to approximate flue gas concentrations in μg/dscm multiply by 0.11 for site E, 0.212 for site F, 0.482 for site G, 0.030 for site H, 0.24 for site I, 1.5 for site J, and 0.16 for site K.

Note: Superscripts indicate test numbers. For test-specific boiler operating conditions, refer to Section 3. Numbers in parentheses are arithmetic averages for a given test.

TABLE 48. TRICHLOROETHYLENE (TCE) EMISSION RESULTS, μg/s[a]

Site	Boiler type	Primary fuel	Low load	Nominal load			High load				Range	Average
E	WT	No. 6 oil for tests 3, 4, 5, 6, and 7 Gas for test 8	16-81^{6} (49)	73-240^{3} (140)	22-46^{4} (36)	30-59^{5} (47)	11-58^{8} (35)	120-680^{7} (470)			11-680	130
F	FT	No. 6 oil		0-106^{2} (42)	40-85^{3} (63)	26-30^{4} (28)					0-106	44
I	WT	Natural gas		2.5-8.6^{2} (4.6)	2.5-3.1^{4} (2.7)						2.5-8.6	3.7
J	FT	None	0.8-12^{5} (4.6)	0.2-0.7^{1} (>0.33)	1.4-5.3^{3} (>3.1)			0.5-1.4^{2} (0.8)	0.3-0.8^{4} (0.5)	0.6-0.8^{6} (0.7)	0.2-5.3	0.91
K	WT	No. 6 oil		7.0-12^{2} (8.9)							7.0-12	8.9

[a] In order to convert emission rates to approximate flue gas concentrations in μg/dscm multiply by 0.11 for site E, 0.212 for site F, 0.24 for site I, 1.5 for site J, and 0.16 for site K.

Note: Superscripts indicate test numbers. For test-specific boiler operating conditions, refer to Section 3. Numbers in parentheses are arithmetic averages for a given test.

TABLE 49. CHLOROBENZENE (Clϕ) EMISSION RESULTS, μg/s^{a}

Site	Boiler type	Primary fuel	Low load	Nominal load				High load			Range	Average
E	WT	No. 6 oil for tests 3, 4, 5, 6, and 7 Gas for test 8	46-82^{6} (64)	35-390^{3} (190)	0-13^{4} (3.0)	0-52^{5} (29)	0-23^{8} (7.3)	0-190^{7} (63)			0-390	59
F	WT	No. 6 oil		1.9-25^{2} (14)	16-20^{3} (18)	12-14^{4} (13)					1.9-25	15
H	WT	Pulverized coal						1.3-7.4^{2} (4.7)	1.2-6.8^{3} (3.1)	3.2-17^{4} (12)	1.3-17	6.6
I	WT	Natural gas		16-110^{2} (44)	1.3-19^{4} (12)						1.3-110	28
J^{b}	FT	None	0^{5}	0-72^{1} (24)	^{3} 0			0-290^{2} (96)	0-160^{4} (80)	18-100^{6} (59)	0-290	43
K	WT	No. 6 oil		1.0-1.9^{2} (1.4)							1.0-1.9	1.4

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[a] In order to convert emission rates to approximate flue gas concentrations in μg/dscm multiply by 0.11 for site E, 0.21 for site F, 0.030 for site H, 0.24 for site I, 1.5 for site J, and 0.16 for site K.

[b] Emissions from modified EPA Method 5 results blank corrected.

Note: Superscripts indicate test numbers. For test-specific boiler operating conditions, refer to Section 3. Numbers in parentheses are arithmetic averages for a given test.

TABLE 50. TOLUENE EMISSION RESULTS, µg/s^a

Site	Boiler type	Primary fuel	Low load	Nominal load	High load	Range	Average
B^b	FT	Natural gas	2.9^2 5.0^3 1.6^4			1.6-5.0	3.2
D	WT	No. 6 oil	NA^5 580-860^6 (720) 530-2,300^7 (1,300)			530-2,300	1,000
E	WT	Natural gas	3,800-7,000^9 (5,400)			3,800-7,000	5,400
F	WT	No. 6 oil		72-420^2 (270) 93-130^3 (110) 29-40^4 (35)		29-420	140
I	WT	Natural gas		13-51^2 (33) 14-36^4 (23)		13-51	28
J^b	FT	None	39-320^5 (150)	0-110^1 (38) 0-450^3 (200)	0-1,400^2 (460) 64-280^4 (180) 140-830^6 (490)	0-1,400	250
K	WT	No. 6 oil		8.5-20^2 (15)		8.5-20	15

[a] In order to convert emission rates to approximate flue gas concentrations in µg/dscm multiply by 2.7 for site B, 0.16 for site D, 0.11 for site E, 0.212 for site F, 0.24 for site I, 1.5 for site J, and 0.16 for site K.

[b] Emissions from modified EPA Method 5 results blank corrected. Corresponds to generally minute concentrations in waste feed.

Note: Superscripts indicate test numbers. For test-specific boiler operating conditions, refer to Section 3. Numbers in parentheses are arithmetic averages for a given test.

NA -- not analyzed due to loss of samples.

Table 45, carbon tetrachloride concentration based on ppm times (H_W/H_T) for site G was one order of magnitude greater than all other test sites. This one order of magnitude appears to have resulted in an equal increase in emission rate compared to other test sites.

Both site H and I waste fuels contributed a minor fraction of the total heat input to the boiler. Therefore, carbon tetrachloride on a ppm x (H_W/H_T) basis were the lowest for these test sites. Average emissions for these sites were correspondingly low, 15 to 25 μg/s. Site I staged combustion results showed essentially no effect on the amount of carbon tetrachloride breakthrough.

Site J was the second firetube boiler tested for destruction of chlorinated organics. However, in contrast to site G, the amount of carbon tetrachloride was one order of magnitude lower than site G. Emission results at various boiler loads and excess air levels showed statistically insignificant changes. Measured emissions were near detection limits of the analysis. Site K showed emission rates in the range of those measured for the other oil-fired watertube boilers.

Trichloroethylene

Trichloroethylene emissions show trends similar to those described for carbon tetrachloride. Trichloroethylene emissions for sites E and F were generally higher than for carbon tetrachloride, however. Since trichloroethylene input rates were essentially similar to those for carbon tetrachloride the anticipated DRE's were likely to be lower.

Results for sites I, J, and K do not show these measured emission rates, however. Site average emission rates were generally lower than carbon tetrachloride. However, the staged combustion test (no. 2) for site I and the low load-high excess air test (no. 5) for site J possibly showed higher emission rates than other tests. This may indicate a greater sensitivity of trichloroethylene to these less favorable thermal destruction environments.

Chlorobenzene

Table 49 indicates that chlorobenzene emissions for site E were on the same order of magnitude as the trichloroethylene. Similar emission trends with respect to individual test sites are also noticeable. Since chlorobenzene input rates at site E were nearly equal to those of trichloroethylene, the anticipated DRE's are likely to be about the same as those for trichloroethylene. Again, test 6 (low load), test 3 (high smoke), and test 7 (high load) showed the highest emission rates.

Site F results indicate chlorobenzene emissions generally lower than either carbon tetrachloride or trichlorobenzene. However, chlorobenzene inputs were also lower than the other two compounds. Site H, I, J, and K results are also in line with those for trichloroethylene and carbon tetrachloride with the noticeable exception of the high load tests for site J. These tests were generally much higher in chlorobenzene emissions with no discernable impact of the high excess air condition (test no. 4). Site J provided the only chlorobenzene POHC data for a firetube boiler.

Toluene

Table 50 summarizes the toluene emission results. Highest toluene firing rates were for sites D, E, and J. Highest emissions were also registered for these sites. The site B toluene input was essentially insignificant compared to the other test sites. The correspondingly low emission rate of 3.2 μg/s (8.8 μg/dscm) is indicative of the low firing rate of toluene.

For site F, the trend of higher emission during tests 2 and 3 compared to test 4 is again evident as with the major chlorinated organics. For site J, high toluene emissions were measured essentially throughout the test program; however evidence of highest emissions is during the high load test as in the case of the chlorobenzene test results. Toluene emission results for sites I and K are essentially equivalent. However, because toluene input to the site K boiler was lower by one order of magnitude, the destruction of toluene at this site is likely to be lower. Compared to site I, site K primary fuel was no. 6 oil with a lower volumetric heat release rate. A small increase of toluene during the staged combustion test at site I was reported. However this increase is not sufficient to suggest a definitive trend.

4.2.3 Summary of Major POHC Emissions

Table 51 summarizes the volatile POHC's for all test sites. In addition to those discussed in the previous section, volatile POHC's also included tetrachloroethylene, 1,1,1-trichloroethane, methylmethacrylate and benzene. Tetrachloroethylene, cofired at site D, resulted in emission rates of 510 to 1,400 μg/s (55 to 150 μg/dscm). This range in emission was not found to correlate either with changing waste fuel POHC concentration or with unsteady burner conditions experienced during a portion of the test program. However, sampling and analytical problems experienced with samples collected at this test site combined with the inability of efficient waste fuel mixing may have hindered the identification of possible emission trends. 1,1,1-trichloroethane emissions at site H were very low. This is in part the result of low waste throughput compared to the total fuel to the boiler.

Emissions of methylmethacrylate at site E show some very interesting trends. These are highlighted in Table 52. During cofiring with chlorinated organics the amount of methylmethacrylate input to the boiler varied between 9,400 and 20,000 ppm corrected for the heat input of the waste with respect to the total heat input. However, emissions varied by one or two orders of magnitude. Highest emissions were measured during tests 3 and 4 with average measurements of 4,000 μg/s (490 μg/dscm) and 1,400 μg/s (160 μg/dscm), respectively. Lowest emission rates were measured during tests 2 and 9, 220 μg/s (27 μg/dscm) and 130 μg/s (17 μg/dscm), respectively. What differed tests 2 and 9 from all other tests was not the amount of methylmethacrylate firing rate nor the primary fuel but the amount of chlorinated organics

TABLE 51. SUMMARY OF MAJOR VOLATILE POHC EMISSIONS

Compound	Site	No. of tests	ppm $\frac{H_W}{H_T} \times 10^3$	Emission range		Average emission	
				µg/dscm	µg/s	µg/dscm	µg/s
Carbon tetrachloride	E	6	5.8-12	0-7.8	0-97	3.3	29
	F	3	2.0-3.0	0.91-29	4.3-136	7.9	37
	G	3	40-50	25-380	53-800	110	230
	H	3	1.0-1.2	0-1.7	0-57	0.45	15
	I	2	1.2-1.7	3.5-7.7	16-34	5.8	25
	J	6	4.8-5.0	0.36-23	0.3-12	5.6	3.5
	K	1	4.0-5.5	1.6-3.8	10-25	3.0	18
Trichloroethylene	E	6	6.0-12	1.4-54	11-680	15	130
	F	3	0.78-6.1	0-23	0-106	9.4	44
	I	2	1.1-1.6	0.6-1.9	2.5-8.6	0.9	3.7
	J	6	10-20	0.38-27	0.2-5.3	3.2	0.91
	K	1	4.0-4.5	1.1-2.3	7.0-12	1.5	8.9
Chlorobenzene	E	6	3.5-7.5	0-48	0-390	6.7	59
	F	3	0.13-0.58	0.4-5.3	1.9-25	3.2	15
	H	3	1.1-1.3	0.04-0.51	1.3-17	0.20	6.6
	I	2	2.3-2.8	0.3-24	1.3-110	6.3	28
	J	6	5.0-5.5	0-360	0-290	57	43
	K	1	4.5	0.2-0.3	1.0-1.9	0.2	1.4
Toluene	B	1	0.002	4.8-13	1.6-5.0	8.8	3.2
	D	3	450	83-360	530-2,300	160	1,000
	E	1	440	500-920	3,800-7,000	710	5,400
	F	3	0.46-1.2	6.2-89	29-420	30	140
	I	2	2.2-3.2	3.1-13	13-51	6.7	28
	J	6	970-980	0-1,800	0-1,400	370	250
	K	2	1.8-2.4	1.2-8.8	8.5-54	3.8	24
Tetrachloroethylene	D	3	8.0-90	55-150	510-1,400	85	790
1,1,1-Trichloroethane	H	3	0.82-0.96	0-0.51	0-17	0.18	5.8
Methylmethacrylate	E	8	7.4-67	0-940	0-8,300	120	1,100
Benzene	I	2	1.1-1.7	32-120	130-440	53	220
	K	2	1.0-1.5	5.1-450	35-2,800	140	830

TABLE 52. EMISSION TRENDS OF METHYLMETHACRYLATE AT SITE E

Test	Primary fuel	Load	Total Cl- to the boiler (ng/J)	Amount in the waste (ppm $H_W/H_T \times 10^3$)	Methylmethacrylate emissions		Test comments
					µg/s	µg/dscm	
2	No. 6 oil	Nominal	7.5	7.4	150-250 (220)	19-31 (27)	Steady-state operation, no smoke
3	No. 6 oil	Nominal	330	11	280-8,300 (4,000)	34-1,000 (490)	Frequent smoke episodes
4	No. 6 oil	Nominal	300	9.4	17-4,100 (1,400)	1.9-460 (160)	Occasional smoke episodes
5	No. 6 oil	Nominal	380	14	94-770 (370)	11-87 (42)	Occasional smoke episodes
6	No. 6 oil	Low	730	20	220-1,200 (710)	34-190 (110)	Steady-state operation, no smoke
7	No. 6 oil	High	290	9.0	0-1,400 (880)	0-110 (70)	Occasional smoke episodes and constant visible plume
8	Natural gas	Nominal	420	12	110-1,900 (720)	14-240 (90)	Continuous visible plume but no smoke alarm
9	Natural gas	Low	0	67	0-280 (130)	0-37 (17)	Continuous visible plume but no smoke alarm

injected with the waste fuel as well as the burner operation. Both chlorine and smoke generation (caused by an unstable burner condition or insufficient combustion air) have detrimental effects on the destruction of organic compounds. Tests 3, 4, 7, and 8 showed periods of high smoke or visible emissions. Although an attempt was specifically made to avoid testing during these upset conditions the impact of burner operation on the destruction of methylmethacrylate is clearly evident. These trends in emission rates of methylmethacrylate are similar to those of chlorinated organics especially those indicating increased emissions with transient burner operations and smoke generation.

Benzene emissions measured for POHC destruction at sites I and K were generally high in the range of 200 to 830 μg/s (53 to 140 μg/dscm). No benzene emission trends were evident with the data available. Staged combustion at site I (test 2) did not produce a consistent increase in benzene emissions. Benzene is often a contaminant of the Tenax sorbent caused by the decomposition of the organic sorbent at ambient conditions. Therefore, these emission results should be interpreted with caution.

Table 53 summarizes emissions of semivolatile POHC's and other semivolatile and nonvolatile organics tracked for DRE determination. Except for phenol no two test sites burned the same compound. Therefore it is impossible to identify any site-dependent emission trends of any given compound. For phenol, the input rate to the site C boiler was significantly greater than that of site A. Since phenol emissions were similar for these two test sites, much greater phenol destruction was achieved at site C. Site A creosote waste fuel contained the largest number of identifiable semivolatile organics.

4.3 OTHER ORGANIC EMISSIONS

The laboratory analyses for volatile and semivolatile organics focused on the identification of POHC emissions. This was in line with the principal objective of each test program: to determine POHC DRE. In addition to POHC emissions, flue gas samples at some test sites also analyzed for the presence of other organic compounds. These analyses focused primarily on quantitative identification of volatile and semivolatile priority pollutants listed in Tables 54 and 55, respectively. Gas chromatography spectra by GC/MS was at times also analyzed for semiquantitative identification of yet other organic peaks. The primary intent of these analyses was to identify and quantitate potential organics resulting from the degradation, recombination, partial oxidation or fragmentation of POHC's as a result of incomplete combustion.

The formation of organic compounds commonly referred to as PIC's have been identified during laboratory studies (References 3 and 9). These studies, performed under controlled feed rates of volatile POHC's, thermal environments and residence time, showed that single chlorinated organic compounds can produce several chlorinated PIC's. These PIC's were not limited to simple fragments of the parent POHC but included higher order chlorinated organics.

TABLE 53. EMISSION RESULTS OF SEMIVOLATILE ORGANICS, μg/s[a]

Compound, μg/s[a]	Site A	Site B	Site C	Site D	Site G	Site I
RCRA Appendix VIII						
Phenol	0-220 (60)[b]		28-190 (83)			
Pentachlorophenol	0-44 (20)					
2,4-dimethylphenol	0-13 (<5.6)					
Naphthalene	25-150 (85)					
Bis(2-chloroethyl)ether				0-6.8 (4.7)		
Epichlorohydrin					0	
Nitrobenzene						38-200 (100)
Fluorene	0-34 (11)					
Other organics						
Anthracene	0-14 (9.5)					
Aniline						19-21 (20)
Xylenes		3.9-5.1 (4.7)				
Methylnaphthalenes	1.3-45 (16)					
Biphenyl	<6.3					
Pyrene	0-37 (14)					
Phenanthrene	0-230 (83)					
Methylpyrenes	<5.1					
C_3-alkylbenzene			60-880 (440)			
Methylenebisphenol			<10			

[a] In order to convert emission to μg/dscm multiply by 0.010 for site A, 2.7 for site B, 0.077 for site C, 0.16 for site D, 0.48 for site G, and 0.24 for site I.

[b] Numbers in parentheses are arithmetic averages of emissions for the given site site.

Zeros indicate that emissions were not detected.

TABLE 54. VOLATILE ORGANICS SOUGHT IN GC/MS ANALYSIS[a]

Chlorinated aliphatics

Chloromethane
Dichloromethane
Chloroform
Tetrachloromethane
Chloroethane
1,1-dichloroethane
1,2-dichloroethane
1,1,1-trichloroethane
1,1,2-trichloroethane
1,1,2,2-tetrachloroethane
1,2-dichloropropane
Hexachlorocyclohexane
Vinyl chloride
1,1-dichloroethylene
1,2-dichloroethylene
Trichloroethylene
Tetrachloroethylene
Tetrachloroethylene
Allyl chloride
1,3-dichlopropopene
Chloroprene

Ethers

Ethylene oxide
Propylene oxide

Chlorinated ethers

Epichlorohydrin
2-chloroethyl vinyl ether

Aldehydes

Acetaldehyde
Acrolein

Amines and nitriles

Acrylonitrile

Aromatic hydrocarbons

Benzene
Toluene
Ethyl benzene
o-Xylene
m-Xylene
p-Xylene

Chlorinated aromatics

Chlorobenzene

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[a] For sites D through H only. Detection limits in the range of 1 to 5 ng/l of gas sample.

TABLE 55. SEMIVOLATILE ORGANICS SOUGHT IN THE GC/MS ANALYSIS AND THEIR DETECTION LIMITS[a]

Acid compounds

2,4,6-trichlorophenol	5	2-nitrophenol	5
p-chloro-m-cresol	5	4-nitrophenol	20
2-chlorophenol	5	2,4-dinitrophenol	20
2,4-dichlorophenol	5	4,6-dinitro-o-cresol	20
2,4-dimethylphenol	5	Pentachlorophenol	5
		Phenol	1

Base neutral compounds

1,2,4-trichlorobenzene	1	Benzo(c)phenanthrene	40
1,2-dichlorobenzene	1	Bis(2-chloroethoxy)methane	1
1,2-diphenylhydrazine (as azobenzene)	1	Bis(2-chloroethyl)ether	1
		Bis(2-chloroisopropyl)ether	1
1,3-dichlorobenzene	1	Bis(2-ethylhexyl)phthalate	1
1,4-dichlorobenzene	1	Butyl benzyl phthalate	1
2,4-dinitrotoluene	1	Chrysene	1
2,6-dinitrotoluene	1	Di-n-butyl phthalate	1
2-chloronaphthalene	1	Di-n-octyl phthalate	1
3,3'-dichlorobenzidine	5	Dibenzo(a,h)anthracene	5
3-methyl cholanthrene	40	Dibenzo(c,g)carbazole	40
4-bromophenyl phenyl ether	1	Diethyl phthalate	1
4-chlorophenyl phenyl ether	1	Dimethyl phthalate	1
7,12-dimethyl benz(a)anthracene	40	Fluoranthene	1
N-nitrosodi-n-propylamine	5	Fluorene	1
N-nitrosodimethylamine	NA	Hexachlorobenzene	1
N-nitrosodiphenylamine	1	Hexachlorobutadiene	1
Acenaphthene	1	Hexachlorocyclopentadiene	1
Acenaphthylene	1	Hexachloroethane	1
Anthracene	1	Indeno(1,2,3-cd)pyrene	5
Benzo(ghi)perylene	5	Isophorone	1
Benzidine	20	Naphthalene	1
Benzo(b)fluoranthene	1	Nitrobenzene	1
Benzo(k)fluoranthene	1	Perylene	40
Benzo(a)anthracene	1	Phenanthrene	1
Benzo(a)pyrene	1	Pyrene	1

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[a] In nanograms per microliter injected.

The identification of PIC's during the field test of cofired waste fuels necessitates meeting two important analytical criteria. The first criteria is that the waste fuels are fully characterized and that all volatile and semivolatile priority pollutants are identified and quantitated. Meeting this criteria ensures that organics identified in the flue gas samples are not mistakenly identified as PIC's. During some field test programs this was not easily accomplished, as in the case of site A, because the waste contained a complex mixture of long chain compounds which hindered the identification of compounds in small concentrations. The second criteria for PIC identification necessitates minimizing contamination of samples by field and laboratory organics. Although the analyses of sample blanks provided contamination values used to correct emission values, uncertainties with respect to several PIC's could not always be resolved.

The following sections summarize the emissions of identifiable volatile PIC's. The data which focuses on RCRA Appendix VIII compounds are limited to those test sites where both criteria for PIC identification were most closely met. Since semivolatile PIC emissions were nearly always insignificant compared to volatile PIC's they are not reported here. Detailed emission rates for all organics are provided in Volume II.

4.3.1 Flue Gas Volatile Organics

Tables 56 through 59 summarize available PIC emission data for test sites D, E, F, and G. In addition to the emission rates of identifiable PIC's, each table lists the POHC's in the waste fuel as well as test-averaged POHC feed rates and emission rates. The emissions of PIC's for these test sites included several chlorinated organics. These were primarily 1,1,1-trichloroethane, tetrachloroethylene, chloroform, chloromethane, 1,2-dichloroethane, and methylene chloride generally having emissions from as low as 50 μg/s to as high as 20 mg/s. Methylene chloride, due to its widespread use in both field and laboratory test environments, is often considered an inherent contamination and thus not a clearly identifiable PIC.

Other chlorinated organics included 1,2-dichloropropane, 1,1-dichloroethylene, trans-1,3-dichloropropelyne, chloroethane, and 1,1,2,2-tetrachloroethane generally detected for site F and having emission rates of less than 50 μg/s. Chlorobenzene was an identifiable PIC at site G and was not detected in the chlorinated fuel. Similarly, carbon tetrachloride and trichloroethylene were apparent PIC's at site D whose waste fuel did not contain these compounds. Toluene and benzene were among the highest emission rate compounds detected for sites E and F, often exceeding 1,000 μg/s. Toluene emissions were generally greater than benzene except when toluene was a POHC at site F. Some site-specific trends can be summarized as follows.

Site D provides the least reliable data on PIC emissions because of several sampling and analytical difficulties experienced with an earlier version of the current VOST. PIC emissions were consistently attributed to toluene, benzene, methylene chloride, chloroform, 1,1,1-trichloroethane, and

TABLE 56. SUMMARY OF SELECTED VOLATILE PIC'S -- SITE D

				Test average emissions of selected PIC's, µg/s[a]											
					Toluene[b]										
Test	POHC's in waste fuel	POHC firing rate, mg/s	Test average POHC emissions, µg/s	Benzene	PCE	Carbon tetrachloride	1,1,2-TCA	DCM	Chloroform	TCE	1,1,1-TCA	1,2-DCA	1,1-DCE	$\sum$ PIC's µg/s	$\frac{\sum \text{PIC's}}{\sum \text{POHC's}}$
2	Tetrachloroethylene	77,900	880	680	750	200	110	2,100	360	30	260	64	360	4,900	5.6
3	Tetrachloroethylene	33,600	630	570	430	270	150	1,600	290	12	160	50	92	3,600	5.7
4	Tetrachloroethylene	19,600	860	220	740	0	0	6,000	120	25	140	0	350	7,700	9.0
5	Bis(2-chloroethyl)ether	7,500	3	0	590	0	0	1,800	410	15	110	26	130	3,100	310
	Toluene	180,000	5												
6	Bis(2-chloroethyl)ether	7,500	4	50	600	94	47	860	160	28	200	0	110	2,900	4.0
	Toluene	180,000	720												
7	Bis(2-chloroethyl)ether	7,500	7	150	50	0	0	0	210	0	46	0	0	1,800	1.4
	Toluene	180,000	1,300												

[a] PCE: tetrachloroethylene; 1,1,2-TCA = 1,1,2-trichloroethane; DCM = dichloromethane (methylene chloride); TCE = trichloroethylene; 1,1,1-TCA = 1,1,1-trichloroethane; 1,2-DCA = 1,2-dichloroethane; 1,1-DCE = 1,1-dichloroethylene.

[b] Data refers to toluene emissions as a PIC for tests 2, 3, and 4 and tetrachloroethylene as a PIC for tests 5, 6, and 7.

TABLE 57. SUMMARY OF SELECTED VOLATILE PIC'S -- SITE E

Test	POHC's in waste fuel	POHC firing rate, mg/s	Test average POHC emissions, μg/s	Test average emissions of selected PIC's, μg/s[a]							∑ PIC's[b] μg/s	Σ PIC's / ∑ POHC's
				1,1,1-TCA	PCE	1,1,2,2-PCA	Toluene	Benzene	Chloroform	Chloromethane		
2	Methylmethacrylate	6,670	220	280	1,100	130	3,400	76	34	--	5,000	23
3	Carbon tetrachloride	6,550	29	--	500	--	1,300	180	--	--	2,000	0.46
	Trichloroethylene	6,790	140									
	Chlorobenzene	3,900	190									
	Methymethacrylate	8,870	4,000									
4	Carbon tetrachloride	7,480	18	52	630	70	2,000	200	45	--	3,000	2.1
	Trichloroethylene	7,660	36									
	Chlorobenzene	4,140	4									
	Methylmethacrylate	8,600	1,400									
5	Carbon tetrachloride	7,290	21	200	800	--	1,780	480	73	--	3,300	7.1
	Trichloroethylene	7,240	47									
	Chlorobenzene	4,030	29									
	Methylmethacrylate	12,450	375									
6	Carbon tetrachloride	7,620	73	170	870	--	2,000	410	200	--	3,700	4.1
	Trichloroethylene	7,360	49									
	Chlorobenzene	4,690	64									
	Methylmethacrylate	12,100	710									
7	Carbon tetrachloride	8,340	33	800	9,500	180	12,000	3,600	21,000	--	47,000	33
	Trichloroethylene	7,740	470									
	Chlorobenzene	4,770	63									
	Methylmethacrylate	11,800	880									
8	Carbon tetrachloride	6,790	12	77	2,200	--	4,500	910	5,800	--	13,500	17
	Trichloroethylene	6,030	35									
	Chlorobenzene	3,660	7.7									
	Methylmethacrylate	9,440	720									
9	Methylmethacrylate	27,800	130	320	2,000	--	--	1,000	4,200	68	7,600	1.4
	Toluene	180,000	5,400									

[a] 1,1,1-TCA = 1,1,1-trichloroethane; PCE = tetrachloroethylene; 1,1,2,2-PCA = 1,1,2,2-tetrachloroethane.

[b] Additional major volatile organics were: ethylbenzene, methoxybutane, chloromethylbenzene, ethenyl ester propanoic acid, ethylmethylbenzene, xylenes oxybismethane, trimethylbenzene, methoxy propanol detected primarily in the methanol rinses of the impinger condensates. Emissions ranged from 25 to 1,400 μg/s. Total test emissions of these organics ranged from 240 to 18,000 μg/s.

TABLE 58. SUMMARY OF SELECTED VOLATILE PIC'S -- SITE F

Test	POHC's in waste fuel	POHC firing rate, mg/s	Test average POHC emissions, µg/s	Test average emissions of selected PIC's, µg/s[a]												ΣPIC's[b] µg/s	ΣPIC's / ΣPOHC's
				PCE	DCM	1,2-DCA	1,2-DCP	1,1,1-TCA	Benzene	1,1,2,2-PCA	T-1,2-DCE	Chloromethane	Chloroform	T-1,3-DCP	Chloroethane		
2	Carbon tetrachloride Trichloroethylene Chlorobenzene Toluene	547 205 33.9 268	97 63 13 230	3.0	580	--	5.0	110	1,300	22	21	700	650	--	3.8	3,400	8.5
3	Carbon tetrachloride Trichloroethylene Chlorobenzene Toluene	1,030 1,690 194 410	670 96 6.0 48	5.0	9,900	--	--	1,300	260	--	1.0	2,000	9,300	--	32	23,000	28
4	Carbon tetrachloride Trichloroethylene Chlorobenzene Toluene	837 1,400 99.4 131	0 22 13 22	1.4	420	5.9	2.5	--	180	--	--	270	--	31	0.8	910	16

[a] Definitions: PCE = tetrachloroethylene; DCM = dichloromethane (methylene chloride); 1,2-DCA = 1,2-dichloroethane; 1,1,1-TCA = 1,1,1-trichloroethane; 1,1,2,2,-PCA = 1,1,2,2-tetrachloroethane; T-1,2-DCE = trans-1,2-dichloroethylene; T-1,3-DCP = trans-1,3-dichloropropene.

[b] Ethylbenzene was the only other compound detected in the samples. Test average emissions of ethylbenzene from 1 to 18 µg/s.

TABLE 59. SUMMARY OF SELECTED VOLATILE PIC'S -- SITE G

Test	POHC's in waste fuel	POHC firing rate, mg/s	Test average POHC emissions, µg/s	Test average emissions of selected PIC's, µg/s[a]							$\sum$ PIC's[b] µg/s	Σ PIC's / $\sum$ POHC's
				Chloroform	DCM	Chloromethane	Chlorobenzene	1,2-DCA	PCE	DCBM		
1	Carbon tetrachloride Epichlorohydrin Bis(2-chloroisopropyl)-ether	9,740 40,400 107,000	93 0 0	6,000	180	10	390	15	--	660	7,300	78
2	Carbon tetrachloride Epichlorohydrin Bis(2-chloroisopropyl)-ether	9,480 40,400 107,000	460 0 0	2,300	250	750	140	2,400	750	170	6,800	15
3	Carbon tetrachloride Epichlorohydrin Bis(2-chloroisopropyl)-ether	10,400 40,400 107,000	110 0 0	280	--	--	12	100	270	160	820	7.5

[a] Definitions: DCM = dichloromethane (methylene chloride); 1,2-DCA = 1,2-dichloroethane; PCE = tetrachloroethylene; DCBM = dichlorobromomethane.

1,1-dichloroethylene. Tetrachloroethylene was a PIC during tests 5, 6, and 7. These emissions were the same order of magnitude as those of tests 2, 3, and 4 when tetrachloroethylene was a POHC. With the exception of test 5, total PIC's exceeded POHC's by less than one order of magnitude.

For site E, highest emissions of chlorinated PIC's were measured for test 7 and test 8 corresponding to high boiler load and nominal boiler load with natural gas as the primary fuel respectively. Chloroform and tetrachloroethylene were the major chlorinated PIC emissions. It should also be pointed out that chlorinated organics were also detected during tests with nonchlorinated fuels (baseline, test 2 and test 9). Fuel oil burned during the baseline and test 2 contained sufficient chlorine to account for these organic emission rate. For test 9, small amounts of carbon tetrachloride and trichloroethylene were present in the waste fuels. These quantities were also sufficient to account for the total chlorinated PIC's measured. For site E, the total emission rate of identifiable PIC's ranged from about 2 to 47 mg/s. Toluene and benzene accounted for about 13 to 75 percent of these emissions. Total PIC's measured exceeded total POHC's emissions generally from one to two orders of magnitude.

Table 58 summarizes the identifiable PIC emissions for the three cofired tests at site F. Major PIC's included: chloromethane, chloroform, methylene chloride and 1,1,1-trichloroethane. Benzene was the only major nonhalogenated organic PIC. Toluene, whose emissions contrary to site E were lower than benzene, was a waste fuel POHC. Total PIC emissions ranged from about 0.9 to 23 mg/s. Highest emission rates were measured during test 3 corresponding to highest emissions of POHC's: carbon tetrachloride and trichloroethylene. These results tend to indicate that generally higher PIC's are anticipated with higher POHC's emissions or lower POHC destruction efficiency.

Identification of PIC's and emission rates for site G required careful evaluation of analytical results of liquid streams associated with the recovery and HCl scrubbers since these were located upstream of the flue gas sample location. It was estimated that the scrubbers contributed to some PIC emissions because of desorption of chloroform from the make up water. However, test data indicated that the scrubbers also removed some minor amounts of organics such as methylene chloride and chlorobenzene as well as brominated organics. Overall these absorption and desorption or organics did not impact flue gas PIC emissions listed in Table 59 significantly. Site G data show that chloroform was the major PIC. The sum of these emissions ranged from 0.8 to 7.3 mg/s corresponding to about 8 to 80 times more than the breakthrough sum of chlorinated POHC's. Toluene and benzene emissions at site G were minor.

Figure 4 illustrates the relationship of test average POHC DRE versus PIC's for chlorinated organics only. A general trend of higher PIC emissions with greater POHC breakthrough (lower DRE) seems to exist. The plotted data are based on the results tabulated in Table 60. Overall chlorinated PIC's were about 120 times the measured breakthrough of chlorinated POHC's for

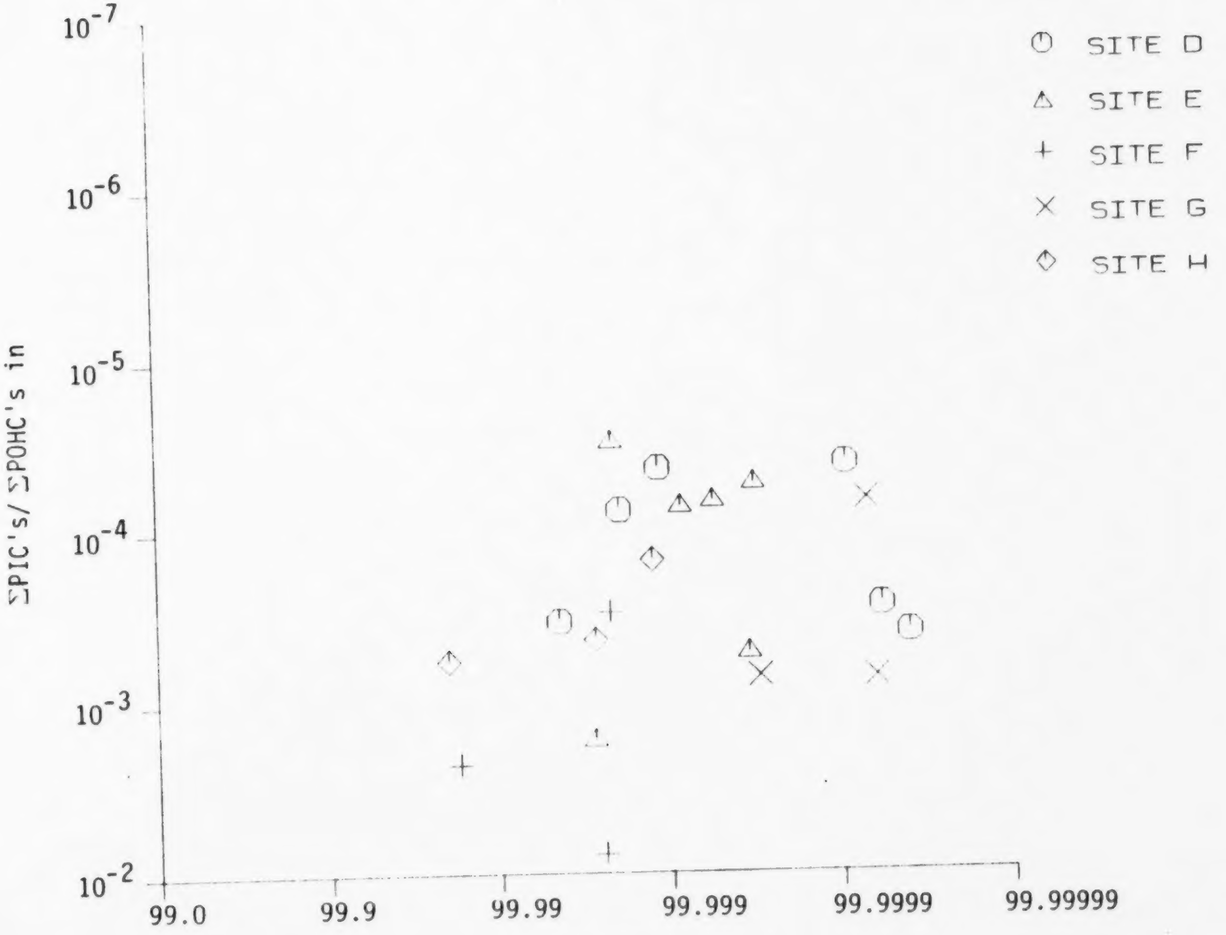

Figure 4. Relationship of volatile chlorinated PIC's versus test average chlorinated POHC DRE sites D, E, F, and G.

TABLE 60. RELATIONSHIP OF VOLATILE CHLORINATED PIC'S VERSUS POHC'S -- SITES D, E, F, G, AND H

Site	Chlorinated waste fuel POHC's	Total chlorinated POHC breakthrough (μg/s)	Total chlorinated PIC's (μg/s)	Selected chlorinated PIC's, percent of total							
				Carbon tetrachloride	Chloromethane	Dichloromethane	Chloroform	1,1,1-TCA and 1,1,2-TCA	Dichloroethylene and dichloroethane	Tetrachloroethylene	ΣPIC's/ΣPOHC's
D	Tetrachloroethylene	630-880 (790)	2,600-7,700 (4,300)	3.6	0	75	6.0	6.4	2.1	--	54
	Bis(2-chloroethyl)ether	3.0-6.8 (4.7)	330-3,100 (1,800)	1.7	0	49	14	7.5	4.4	23	380
E	Carbon tetrachloride, chlorobenzene, and trichloroethylene	56-570 (220)	500-32,000 (7,400)	--[a]	0	NA	61	2.9	0	33	34
F	Carbon tetrachloride, chlorobenzene, and trichloroethylene	51-133 (85)	700-23,000 (8,400)	--	12	43	39	5.7	0.09	0.04	99
G	Carbon tetrachloride, epichlorohydrin, and bis (2-chloroisopropyl) ether	95-307 (170)	710-7,300 (4,900)	--	5.2	2.9	58	0	17	6.9	29
H	Carbon tetrachloride, chlorobenzene, and 1,1,1-trichloroethane	290-4,100 (1,600)	4,000-12,000 (6,900)	--	92	0	2.7	0.5	0	2.6	4.3
	Average results	4.7-1,600 (570)	1,800-8,400 (6,700)	2.7	18	34	30	3.8	3.9	11	120

[a] Dashes indicate POHC in the waste fuel.

NA -- not analyzed.

these test sites. Figure 5 illustrates a similar trend for total measured PIC's (including toluene and benzene) versus test average POHC DRE.

4.3.2 Other Discharge Streams Organics

Liquid discharge streams were sampled at site G where two recovery and HCl scrubbers treated the flue gas for removal of acid emissions. Tables 61 and 62 summarize the emissions of major volatile organics detected in both scrubber discharge and makeup water streams. Significant quantities of methylene chloride, chloroform and brominated organics were measured in the makeup and discharge streams from both scrubber towers. The presence of chlorinated organics, e.g. chloroform, in the makeup water is not surprising because river water was chlorinated at the plant to suppress algae growth. In both scrubber towers chloroform in the makeup water was much higher than the chloroform accounted by the discharges. This indicates a possible contribution of makeup water chloroform to flue gas emissions which were measured in the range of 280 to 5,000 μg/s. On a total mass basis, methylene chloride and brominated organics were scrubbed from the flue gas. Other minor organics detected in the scrubber discharger were carbon tetrachloride, POHC in the boiler feed at site G, and 1,2-dichloroethane. Their emissions were generally less than 10 μg/s. Acid recovery and HCl control by the dual scrubber system exceeded 99 percent efficiency.

Organic analyses for semivolatile compounds were also performed on site A and H ash discharge streams. Results generally indicate low or nondetectable concentrations of organic priority pollutants. These results are in agreement with several other studies which indicate that flue gas organic emissions dominate the total organic emissions from a combustion source. Detailed analyses of site A and H discharge streams are provided in Volume II of this report.

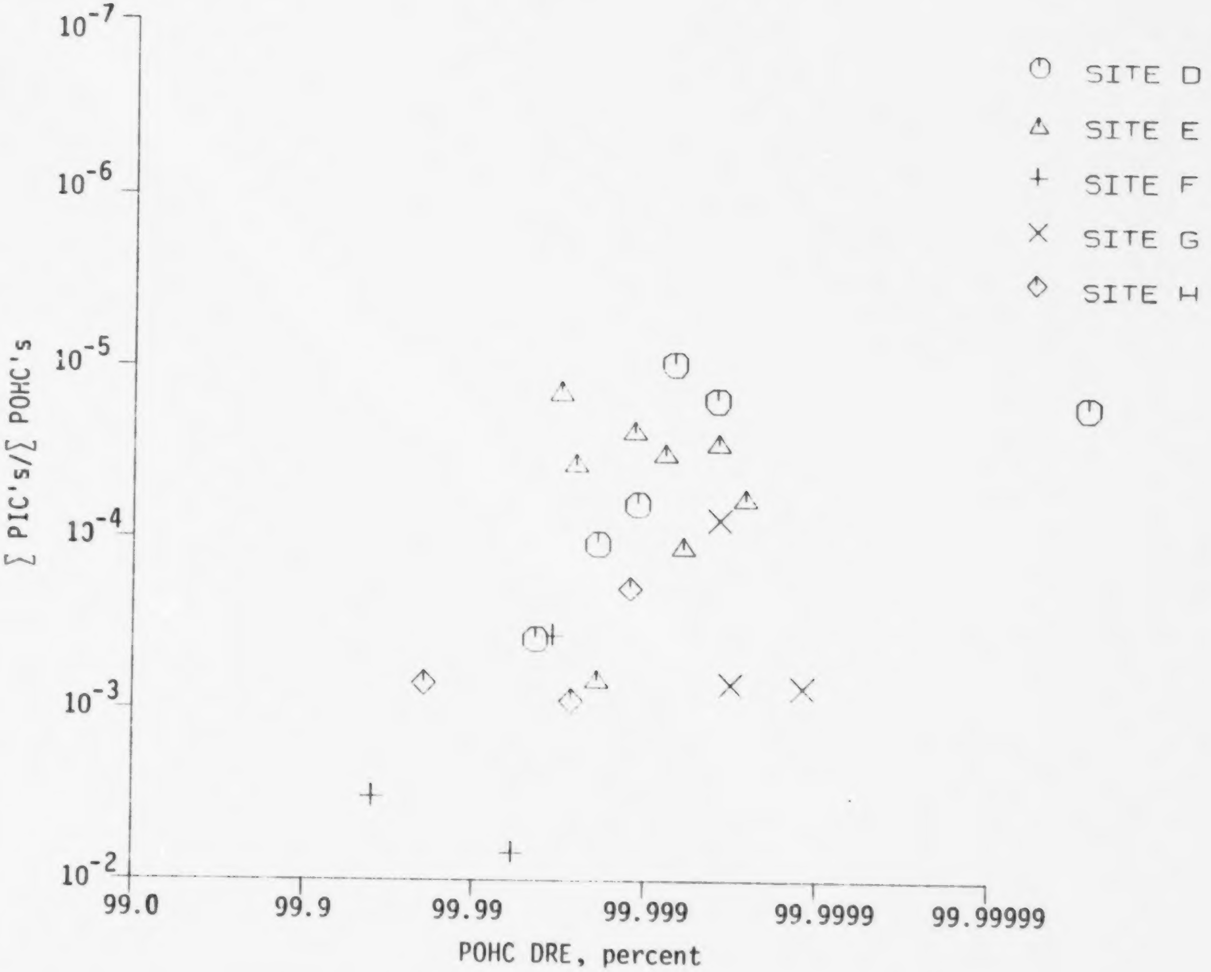

Figure 5. PIC emissions versus test average POHC DRE.

TABLE 61. MASS FLOWRATES OF ORGANICS IN MAKEUP WATER AND RECOVERY SCRUBBER DISCHARGE STREAMS, µg/s[a] -- SITE G

Compound	Makeup water (in)	Recovery scrubber discharge (out)	(Out-in)
Methylene chloride	180 to 710[b] (360)	5.4 to 7,000 (2,500)	2,600
Chloroform	250 to 410 (320)	ND to 5.4 (1.8)	-320
Bromodichloromethane	120 to 210 (160)	ND to 16 (9.1)	-150
Chlorodibromomethane	45 to 590 (230)	ND to 166 (108)	-100
Bromoform	ND to 1,230 (420)	ND to 540 (190)	-90

[a] Organic specie flowrates are based on stream flowrates of 5.2 l/s (83 gpm).

[b] Ranges in flowrates are based on analytical results of each test. Number in parentheses represents the arithmetic average of the range given.

ND = not detected; less than 6 µg/s.

TABLE 62. MASS FLOWRATES OF ORGANICS IN MAKEUP WATER AND HCl SCRUBBER DISCHARGE STREAMS, µg/s[a] -- SITE G

Compound	Makeup water (in)	Recovery scrubber discharge (out)	(Out-in)
Methylene chloride	280 to 1,100[b] (570)	320 to 570 (430)	-60
Chloroform	380 to 630 (500)	220 to 280 (250)	-250
Bromodichloromethane	190 to 330 (250)	850 to 1,000 (920)	670
Chlorodibromomethane	70 to 920 (360)	2,400 to 3,700 (3,100)	2,700
Bromoform	ND to 1,900 (660)	2,800 to 4,400 (3,300)	2,600

[a] Organic specie flowrates are based on stream flowrates of 10 l/s (160 gpm).

[b] Ranges in flowrates are based on analytical results of each test. Number in parentheses represents the arithmetic average of the range given.

ND = not detected; less than 10 µg/s.

SECTION 5

POHC DESTRUCTION EFFICIENCY

Quantification of the destruction efficiency of individual waste fuel POHC's was the main objective of these test programs. This section is devoted to the presentation and interpretation of DRE results obtained from each of the 11 test sites under combustion conditions investigated. By definition, the DRE of any POHC is based only on the flue gas POHC emission rate measured in the stack, downstream of any control device. Therefore, results presented here do not account for emission rates from solid or liquid discharge streams. However, these streams account for a minor fraction of the total organic discharged with the flue gas. Furthermore, it is important to point out that credit is not given for measured baseline emissions. DRE's aower than 99.990 percent indicate failure to meet the current regulation governing hazardous waste incinerators.

5.1 SUMMARY OF RESULTS

The bulk of the DRE results is for the volatile POHC's: carbon tetrachloride, trichloroethylene, chlorobenzene, and toluene. With some variation, all three chlorinated compounds were added to the waste fuels of sites E through K. Toluene was a common POHC found in the waste fuels available at several test sites. Therefore, the DRE's developed for these POHC's offer a comparative analysis of destruction efficiency achieved among different boiler design, primary fuels, and operating conditions.

Tables 63 through 67 summarize the DRE results for these and other volatile POHC's at sites E, F, and H through J. The following sections provide a summary discussion of these results. DRE results for the other test sites are discussed in Section 5.1.6.

5.1.1 Site E Results

Table 63 shows that the weighted average DRE for all volatile POHC's under all combustion conditions investigated was 99.995 percent. With the exception of test 3 which resulted in a total mass average DRE of less than 99.990 percent, mass average DRE's were all greater than or equal to 99.994. However, the range in measured DRE's (generally three measurements were available for each test) clearly showed that the variation in POHC destruction can be significant; i.e., from 99.90 to 99.99999 percent. Overall, these results show three important trends:

TABLE 63. VOLATILE ORGANICS DRE'S -- SITE E

Test	Average CO, ppm	Average NO_x, ppm	Recorded boiler operating conditions	DRE's of volatile POHC's (percent)[a]						
				Carbon tetrachloride	Trichlor-ethylene	Chloro-benzene	Methyl-methacrylate	Toluene	Range	Weighted average
2	92	325	Nominal load and excess air. No major operational upsets.				99.996- 99.998 (99.997)		99.996- 99.998	99.997
3	112	350	Nominal load and excess air. Several smoke episodes and waste flow surges.	99.998- 99.99996 (99.9995)	99.996- 99.998 (99.998)	99.990- 99.9991 (99.995)	99.90- 99.997 (99.95)		99.90- 99.99996	99.98
4	109	340	Nominal load and excess air. Fewer smoke episodes compared to test 3. Better waste flow control.	99.9996- 99.99998 (99.9998)	99.9990- 99.9997 (99.9995)	99.9997- 99.99995 (99.99990)	99.95- 99.9998 (99.98)		99.95- 99.99998	99.994
5	106	317	Nominal load and excess air. No major operational upsets.	99.9991- 99.99997 (99.9997)	(99.9994)	99.998- 99.99995 (99.9993)	99.994- 99.9992 (99.997)		99.994 99.99997	99.998
6	94	365	Lower boiler load and nominal excess air. Smoke episodes.	99.9990- 99.9991 (99.9990)	99.998- 99.9998 (99.9993)	99.998- 99.9990 (99.998)	99.990- 99.998 (99.994)		99.990- 99.9998	99.997
7	101	270	High boiler load and nominal excess air (maximum). High stack opacity but few smoke episodes.	99.998- 99.99998 (99.9996)	99.991- 99.998 (99.994)	99.996- 99.99996 (99.998)	99.98- 99.99998 (99.993)		99.98- 99.99998	99.995
8	68	405	Nominal load and excess air. No smoke episodes or operational upsets.	99.9997- 99.99992 (99.9998)	(99.9994)	99.9993- 99.99995 (99.9998)	99.98- 99.9990 (99.992)		99.98- 99.99992	99.997
9	80	124	Low boiler load and nominal excess air. High stack opacity but no smoke episodes.				99.9990- 99.999990 (99.9995)	99.995- 99.998 (99.997)	99.995- 99.999990	99.9990
Weighted average DRE of volatile POHC's				99.998- 99.99998 (99.9996)	99.991- 99.9998 99.998)	99.990- 99.99996 (99.998)	99.90- 99.999990 (99.991)	99.995- 99.998 (99.997)	99.90- 99.999990	99.995

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[a] Numbers in parentheses represent the test average DRE.

TABLE 64. VOLATILE ORGANICS DRE'S -- SITE F

Test	Average CO, ppm	Average NO_x, ppm	Recorded boiler operating conditions	DRE's of volatile POHC's (percent)[a] Carbon tetrachloride	Trichlor-ethylene	Chloro-benzene	Toluene	Range	Weighted average
2	139	254	Progressive coking of oil and waste fuel gun nozzles.	99.98- 99.990 (99.98)	99.95- 99.997 (99.98)	99.95- 99.995 (99.96)	99.8- 99.97 (99.90)	99.8- 99.997	99.96
3	109	268	Continuous coking of both fuel gun nozzles. Sudden shut-off of waste fuel burner.	99.998	99.98- 99.998 (99.994)	99.990- 99.994 (99.992)	99.97	99.98- 99.998	99.993
4	NA	214	Repositioning of waste fuel gun. Sudden shut-off of oil burner.	99.998- 99.9995 (99.9990)	99.998	99.98	99.97- 99.98 (99.97)	99.97- 99.9995	99.996
	Weighted average DRE of volatile POHC's			99.98- 99.9995 (99.995)	99.95- 99.998 (99.996)	99.93- 99.995 (99.98)	99.8- 99.98 (99.95)	99.8- 99.9995	99.98

[a] Numbers in parentheses represent the test average DRE.

NA -- Test data not available.

TABLE 65. VOLATILE ORGANICS DRE'S -- SITE H

				DRE's of volatile POHC's (percent)[a]				
Test	Average CO, ppm	Average NO_x, ppm	Recorded boiler operating conditions	Carbon tetrachloride	1,1,1-Trichlor-ethane	Chloro-benzene	Range	Weighted average
2	127	319	High load and nominal excess air. Low waste-fuel ratio.	99.993- 99.99993 (99.9994)	99.994- 99.99995 (99.9996)	99.991- 99.998 (99.992)	99.991- 99.99995	99.997
3	120	328	High load and nominal excess air. Low waste-fuel ratio.	99.994- 99.99998 (99.9990)	99.995- 99.99998 (99.9990)	99.996- 99.9992 (99.997)	99.994 99.99998	99.998
4	114	344	High load and high excess air. Low waste-fuel ratio.	99.97	99.97- 99.98 (99.97)	99.990	99.97- 99.990	99.98
	Weighted average DRE of volatile POHC's			99.97- 99.99998 (99.98)	99.97- 99.99998 (99.994)	99.990- 99.9992 (99.992)	99.97- 99.99998	99.991

[a] Numbers in parentheses represent the test average DRE.

TABLE 66. VOLATILE ORGANICS DRE'S -- SITE I

Test	Average CO, ppm	Average NO_x, ppm	Recorded boiler operating conditions	DRE's of volatile POHC's (percent)[a]					Range	Weighted average
				Carbon tetrachloride	Trichlor-ethylene	Chloro-benzene	Toluene	Benzene		
2	180	420	Staged combustion air. Normal excess air.	99.9991- 99.9995 (99.9993)	99.9997- 99.99992 (99.99990)	99.991- 99.9994 (99.997)	99.997- 99.9992 (99.998)	99.96- 99.98 (99.97)	99.96- 99.99992	99.998
4	64	1,150	Unstaged combustion air. Normal excess air.	99.9990- 99.9993 (99.9990)	99.99991- 99.99993 (99.99992)	99.998- 99.9991 (99.9990)	99.997- 99.9992 (99.998)	99.97- 99.998 (99.98)	99.97- 99.99993	99.9990
Weighted average DRE of volatile POHC's				99.9990- 99.9995 (99.9993)	99.9997- 99.99993 (99.99991)	99.991- 99.9994 (99.998)	99.997- 99.9992 (99.998)	99.96- 99.998 (99.97)	99.96- 99.99993	99.998

[a] Numbers in parentheses represent the test average DRE.

TABLE 67. VOLATILE ORGANICS DRE'S -- SITE J

Test	Average CO, ppm	Average NO_x, ppm	Recorded boiler operating conditions	DRE's of volatile POHC's (percent)[a]				Range	Weighted average
				Carbon tetrachloride	Trichlor-ethylene	Chloro-benzene[b]	Toluene		
1	108	168	Nominal load and excess air	99.996- 99.9990 (99.997)	99.9997- 99.99993 (99.9998)	99.93- 99.96 (99.95)	99.9996 99.99993 (99.9997)	99.93- 99.99993	99.998
2	142	82	High load and normal excess air	99.998- 99.9993 (99.9990)	99.9997- 99.99991 (99.9998)	99.8- 99.98 (99.94)	99.997- 99.99990 (99.9990)	99.8- 99.99991	99.998
3	10	158	Nominal load and excess air	99.998- 99.9998 (99.9990)	99.998- 99.9994 (99.998)	99.97- 99.98 (99.97)	99.998- 99.9998 (99.9992)	99.97- 99.9998	99.9990
4	87	76	High load and high excess air	99.9996- 99.99992 (99.9998)	99.9998- 99.99993 (99.99990)	99.7- 99.93 (99.8)	99.9994- 99.9998 (99.9996)	99.7- 99.99993	99.9990
5	89	130	Low load and high excess air	99.998- 99.9996 (99.9992)	99.997- 99.9998 (99.9990)	99.97	99.998- 99.9996 (99.9993)	99.97- 99.9998	99.998
6	20	84	High load and normal excess air	99.998- 99.9994 (99.9991)	99.99992- 99.99994 (99.99993)	99.95- 99.99 (99.97)	99.998- 99.9997 (99.9991)	99.95- 99.99994	99.9990
	Weighted average DRE of volatile POHC's			99.996- 99.99992 (99.9990)	99.997- 99.99994 (99.9996)	99.7- 99.99 (99.95)	99.997- 99.99993 (99.9990)	99.7- 99.99994	99.9990

[a] Numbers in parentheses represent the test average DRE.
[b] DRE's for chlorobenzene are primarily based on analytical detection limits for emission rates.

- Test 3 DRE's were generally lower than those recorded for the other tests. The clearest evidence of this is offered by the results obtained with MMA with a test average DRE of 99.95 percent. However, generally lower DRE's were also recorded for chlorinated POHC's, although these still exceeded 99.990 percent.

- The DRE of MMA was consistently lower than that of any other volatile POHC. Test average DRE's for MMA varied from 99.95 percent for test 3 to 99.9995 for test 9. Test average DRE's for other compounds varied from 99.995 to 99.9999 percent. The average DRE for MMA for test 4 also dropped below 99.990 percent.

- The DRE of MMA was consistently lower during cofiring tests where waste fuel had been artificially chlorinated with carbon tetrachloride, trichloroethylene, and chlorobenzene. For tests 2 and 9, with waste fuel void of chlorinated POHC's the DRE was 99.997 and 99.9995 percent, respectively. When the waste fuel was chlorinated, the test average DRE was usually below 99.995 percent.

The lower DRE's for test 3 coincided with boiler operating conditions that led to in-furnace soot formation and several smoke emission episodes. Although test 3 was the first of the tests with chlorinated waste fuel, these smoke emissions are not attributed to this factor, per se. It was clearly evident, however, that higher excess air levels were required with chlorinated fuels following test 2. Furthermore, a sensitivity of smoke generation to waste fuel guns orientation and uneven distribution of waste flow between the two guns also played a role in less favorable destruction conditions. These conditions may have been accentuated by insufficient excess combustion air. During test 4, higher excess combustion air, combined with better control of the waste fuel flow, resulted in fewer cases of smoke emissions. The corresponding DRE's were higher than test 3; however further improvement in MMA DRE was not achieved until test 5.

The constantly lower DRE's for MMA throughout the site E test program can be attributed to two factors. Two other major organic compounds of the waste fuel were α-hydroxy-methylisobutyrate (MOB) and α-hydroxy-methylisobutyrate methylether (MEMOB). These polymers rapidly decompose at high burner temperature to MMA. Therefore, MOB and MEMOB can be viewed as producing MMA as a PIC, or the MMA in the burner zone was actually much higher than that reported based on the MMA concentration of the waste fuel. The destruction of MOB and MEMOB were complete with DRE's well above 99.9999 percent. Another possible explanation of the poor MMA DRE's with chlorinated waste is the flame suppression characteristic of the chlorinated organics. Halogenated organics are typically flame retardants that tend to reduce residence time at elevated temperatures. This, in combination with (1) smoke generation through insufficient mixing and excess air and (2) the formation of the monomer MMA from MOB and MEMOB, may have resulted in the overall poor DRE's for MMA.

The effect of boiler load changes on DRE's during tests 6 and 7 was minimal. Also the change of primary fuel from residual oil to natural gas during test 8 did not result in significant changes in DRE's, with the possible exception of chlorobenzene which showed a DRE increase from 99.998 to 99.9998 percent. This may be the result of reduced formation of chlorobenzene as a PIC from oil combustion as well as higher destruction of the POHC in the waste fuel. In general, carbon tetrachloride showed higher DRE's exceeding 99.9990 in every test regardless of combustion condition or primary fuel. Trichloroethylene and chlorobenzene showed about equal DRE's.

Figures 6 and 7 clearly indicate that CO and NO_x emissions are not definitive surrogates for site E DRE trends. Although test average CO emissions were generally higher during test 3, the large variation in DRE does not provide a clear identification of trends of destruction with CO emissions, with the possible exception of MMA.

5.1.2 Site F Results

Volatile POHC DRE's of site F were generally the lowest of any of the 11 test sites. The overall mass-weighted average DRE for this site was 99.98 percent indicating that test- and compound-specific DRE's were typically below 99.990 percent. A trend of increasing DRE with test number is somewhat evident. This trend coincides with CO emissions and general burner operating conditions. As discussed in section 3, tests 2 and 3 were characterized by unstable burner conditions. This burner instability was traced to improper positioning of both primary and waste fuel guns in the burner ports. This trend in DRE's is also evident for each of the POHC's. Carbon tetrachloride and trichloroethylene showed similar DRE's from 99.98 percent during test 2 to about 99.9990 percent during test 4. Chlorobenzene and toluene DRE's were generally lower than those of carbon tetrachloride and trichloroethylene. However, both chlorobenzene and toluene had lower waste fuel concentrations than the other two POHC's.

5.1.3 Site H Results

Boiler operation during testing at site H was relatively steady at high load. The waste-fuel ratio for this site was very low, in the range of 2 to 4 percent on a heat input basis. Table 65 summarizes the DRE results. Test average DRE for the three spiked POHC's ranged from 99.98 percent for test 4 to about 99.998 percent for tests 2 and 3. The site average DRE was 99.991 percent. DRE's for test 4 were consistently lower than DRE's for the other two tests; in fact, none of the POHC's exceeded a DRE of 99.990 percent. Furthermore, chlorobenzene showed consistently lower DRE's than either carbon tetrachloride or 1,1,1-trichloroethane. Significant levels of chlorobenzene were also measured during the baseline test. This seems to point to a substantial quantity of chlorobenzene as a PIC from fossil fuel combustion. Relatively high levels of chlorobenzene emissions and lower DRE's were also recorded at sites E and F. Boiler operating conditions during test 4 included occasional surges in excess air levels with excess O_2 as high as 12 percent. Other operating conditions of load and waste feed rate did not change sufficiently to be identified as potential causes of lower DRE's for this test.

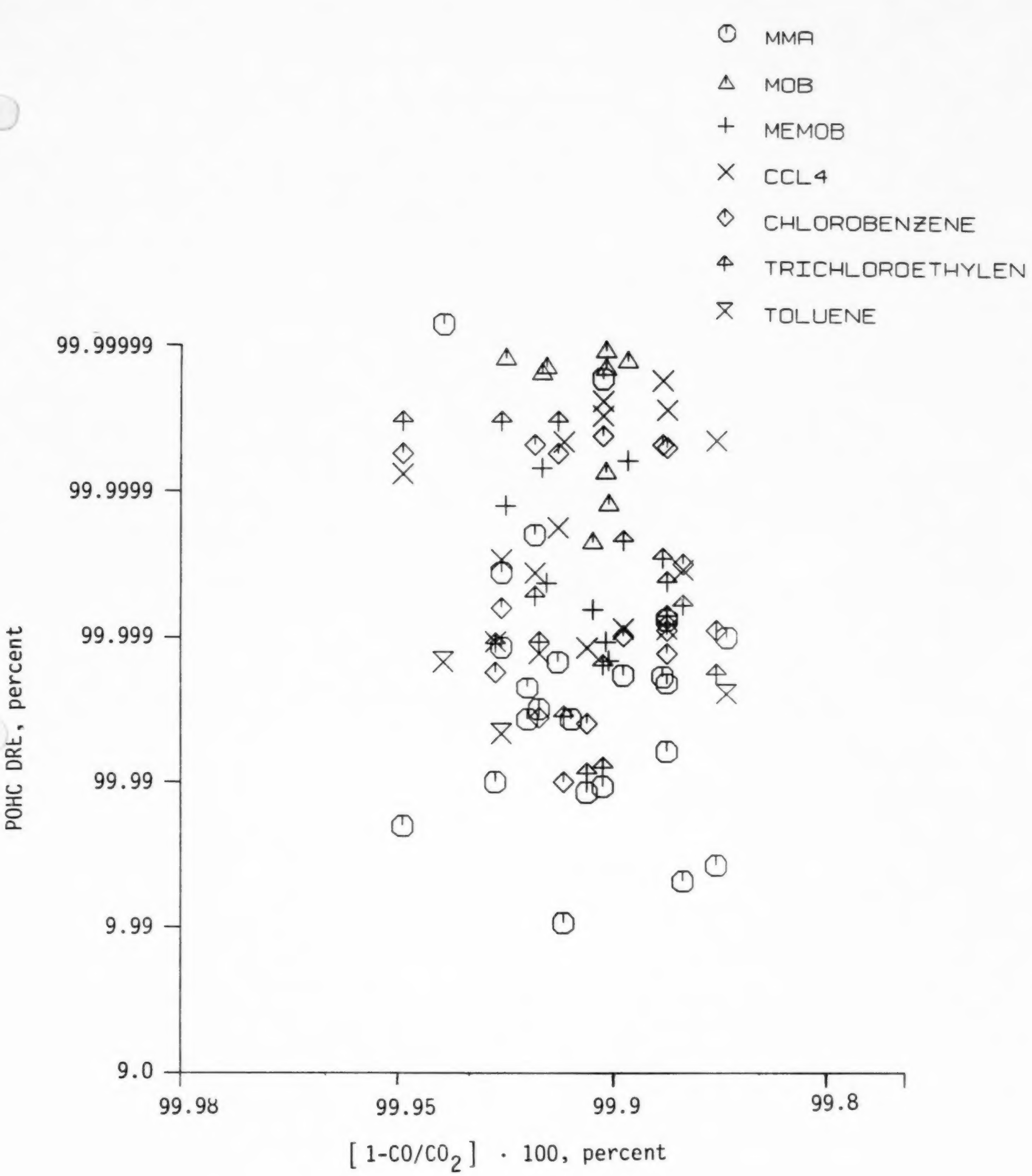

Figure 6. Site E DRE versus combustion efficiency.

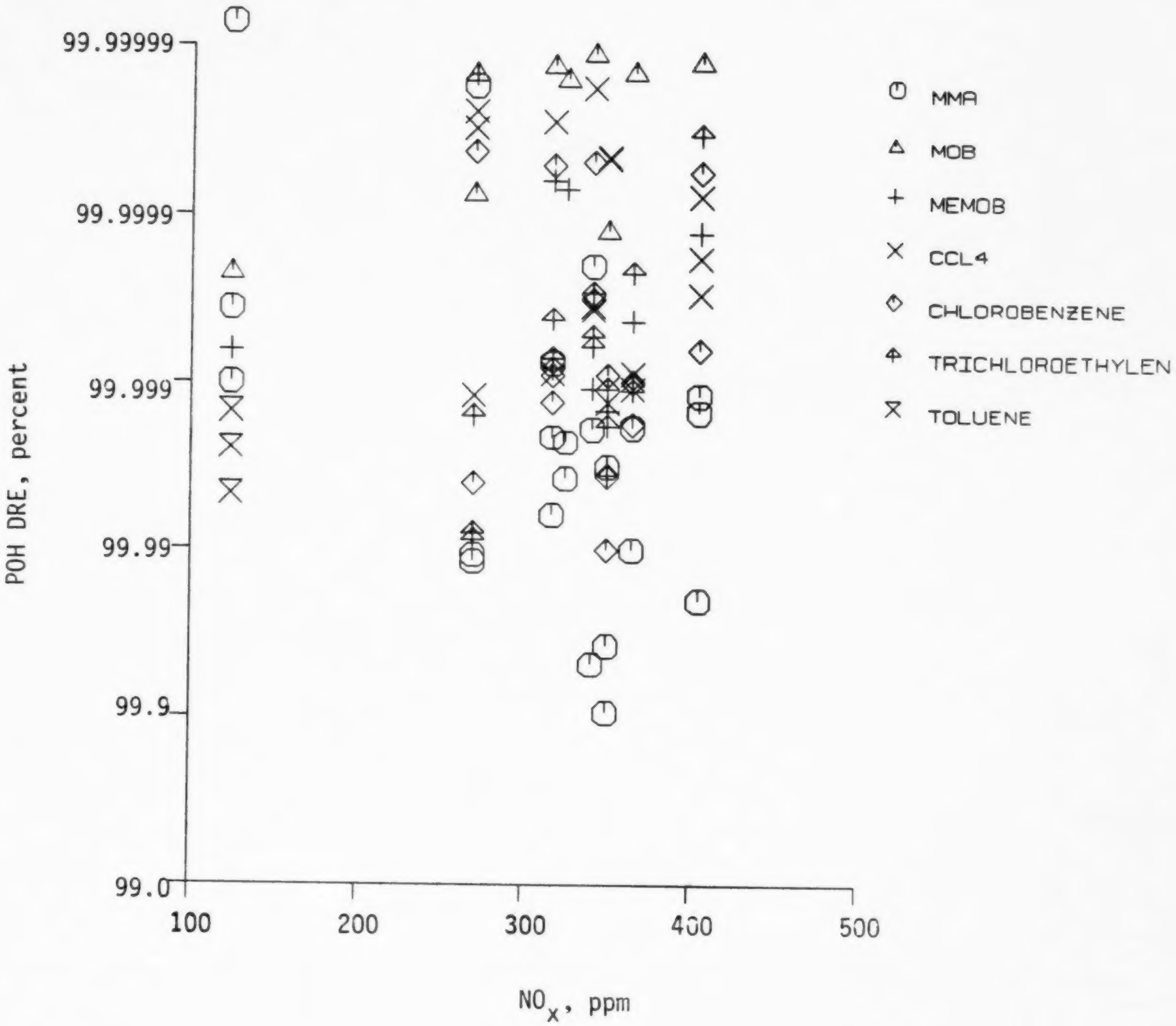

Figure 7. Site E DRE versus NO_x.

5.1.4 Site I Results

At this site, two cofired tests were performed: one with staged combustion air for NO_x reduction and the other with unstaged combustion air. The staged combustion was achieved by biasing the air distribution to the upper burner leaving the lower burner region in a fuel-rich condition. This resulted in a significant reduction in NO_x emissions but a three-fold increase in CO emissions. NO_x emissions at this site were very high due to a large concentration of nitrated organics, namely nitrobenzene and aniline.

Table 66 summarizes DRE results for site I volatile POHC's. The measured DRE's show no significant change in the two combustion modes investigated. The test average DRE's were 99.998 percent for test 2 and 99.9990 percent for test 4. The DRE's of chlorinated POHC's ranged from 99.997 to 99.99992 percent. Again, chlorobenzene DRE's were slightly lower than DRE's of either carbon tetrachloride or trichloroethylene. Benzene DRE's were the lowest of any of the POHC's. However, this result was attributed in part to the inherent contamination of the Tenax-GC sorbent used in the VOST. Since Tenax-GC has been shown to decompose and form benzene, the validity of the benzene DRE's for site I are questionable. Analysis of modified EPA Method 5 samples (XAD-2 sorbent) showed significantly lower benzene emissions, casting further doubt on the validity of the benzene DRE's based on VOST results.

DRE's for aniline and nitrobenzene were 99.9995 and 99.99996 percent, respectively, averaged for both cofired tests. The DRE's of these components did not change appreciably from staged to unstaged combustion conditions.

5.1.5 Site J Results

Table 67 summarizes DRE results for site J. Each of the six tests showed a mass averaged DRE for all volatile POHC's in the range of 99.998 to 99.9990 percent. With the exception of chlorobenzene, the typical test average DRE for the POHC's was greater than 99.9990 percent. The low DRE results for chlorobenzene are due primarily to the high detection limit and lower firing rate for this compound. In reality, chlorobenzene was measured in only 6 of the 17 VOST samples. Variable boiler load and excess air levels did not result in any measurable change in POHC DRE's.

Figures 8 and 9 illustrate DRE results versus combustion efficiency and NO_x emissions, respectively, for site J. For this site the test DRE data can be prepared in two CO or NO_x emission bands. Tests 1, 3, and 5 were higher NO_x tests than tests 2, 4, and 6. Tests 3 and 6 were low CO emission tests. For the most part there is no correlation between DRE and either CO or NO_x. However, both trichloroethylene and chlorobenzene results may indicate some dependence of DRE on these emissions. Generally higher DRE's for these POHC's were obtained during low CO and high NO_x emissions. The trends are not universal, however, and the concept of either CO or NO_x emissions as DRE surrogates remains questionable.

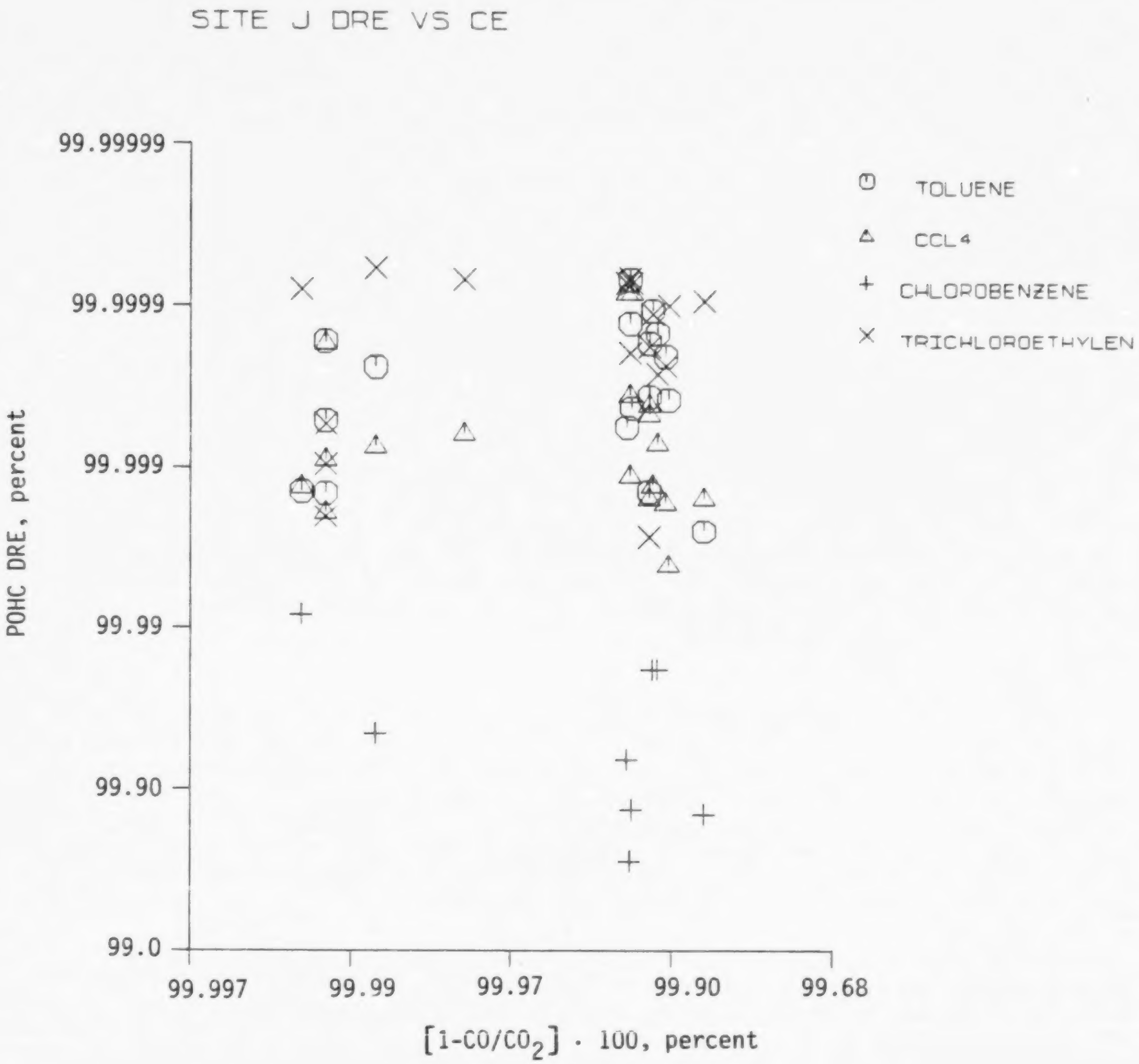

Figure 8. Site J DRE versus combustion efficiency.

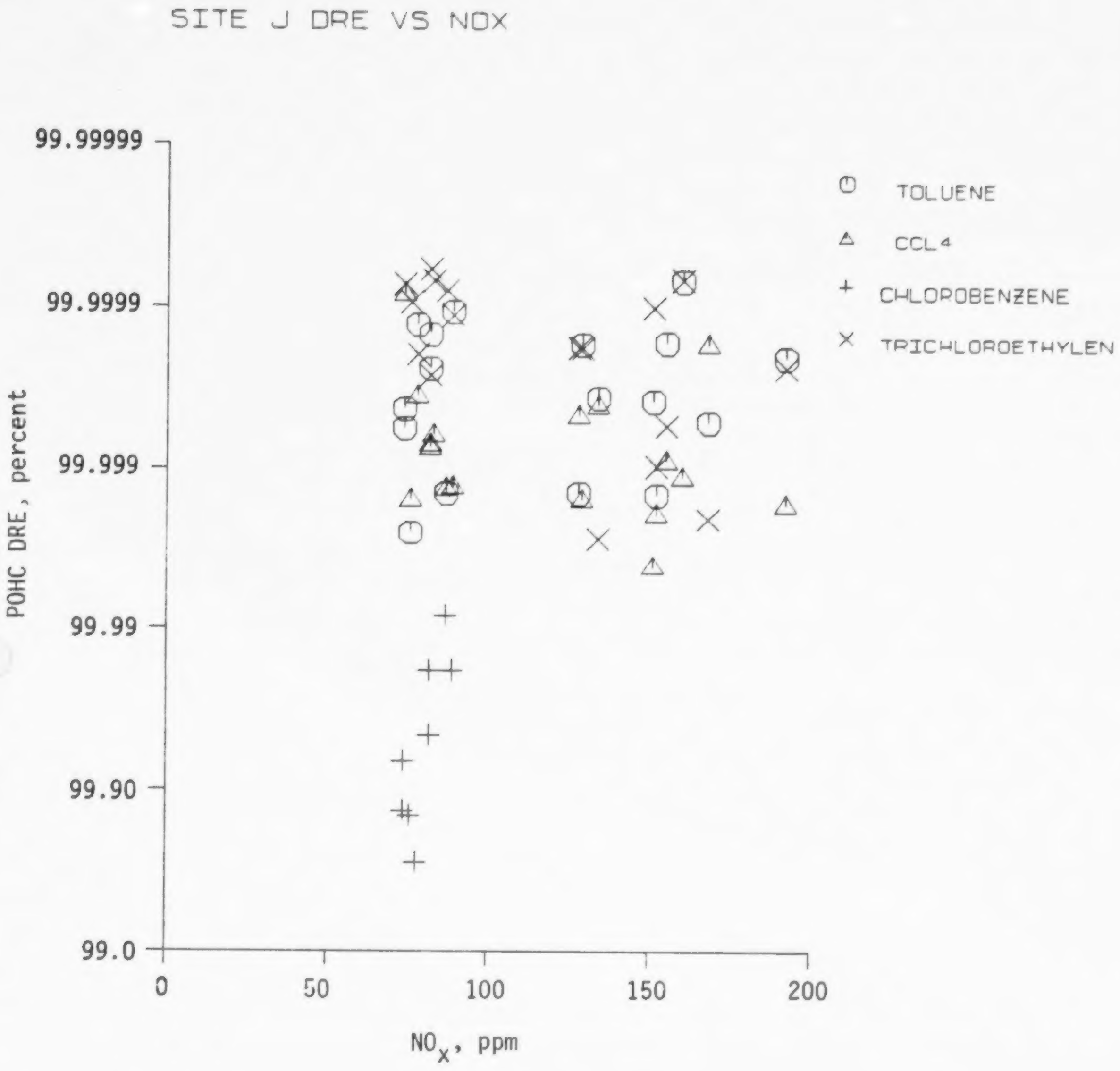

Figure 9. Site J DRE versus NO_x.

5.1.6 Other DRE Results

Table 68 summarizes the DRE's of volatile POHC's for sites D, G, and K. At site D, tetrachloroethylene and toluene were the only volatile POHC's. Measured DRE's ranged from 99.995 to 99.9990 percent, averaging 99.998 percent for tetrachloroethylene and exceeding 99.9990 percent for toluene. High tetrachloroethylene DRE's were obtained in spite of the unstable burner conditions experienced during test 2. However, flue gas measurements were made primarily during steady-state operation, and an attempt was made to purposely avoid sampling during high smoke emissions. At site D, bis(2-chloroethyl)ether was the semivolatile POHC. Its DRE exceeded 99.9999 percent for all tests.

At site G, carbon tetrachloride was the volatile POHC of interest. Its calculated test average DRE ranged from 99.992 to 99.9995 percent. For the entire test program, the mass-averaged DRE for carbon tetrachloride was 99.998 percent. None of the measurements resulted in DRE's of less than 99.990 percent. Boiler operation at site G was steady with no major upsets by either the boiler or scrubbing device. Carbon tetrachloride in the scrubber discharge streams was generally minimal compared to flue gas emissions. Epichlorohydrin and bis(2-chloroisopropyl)-ether were the two semivolatile POHC's of interest at site G. DRE's for these semivolatile organics generally exceeded 99.99990 percent.

DRE's for site K volatile organics were generally greater than 99.9990 percent. Lowest DRE's were for benzene, 99.990 to 99.998 percent (99.996 percent test average). Benzene results are suspect because of the inherent contamination from the Tenax-GC sorbent.

Other DRE results were provided by semivolatile POHC's in the waste fuels at sites A, C, and I. Table 69 summarizes these results. The site A boiler was a wood-fired stoker. The operation of these units is generally accompanied by high excess air levels and high CO emissions. This is characteristic of batch fuel feed and combustion of high-moisture coarse wood waste mixture. The calculated DRE's for semivolatile organics detected in the creosote were generally below 99.990 percent. This is especially the case for phenol, pentachlorophenol, naphthalene, and 2-4 dimethylphenol whose average DRE's ranged from 99.96 to 99.98 percent. Fluorene was the only semivolatile POHC with an average DRE of greater than 99.990 percent. These results may indicate that wood-fired boilers operating under typical conditions such as those recorded at site A may not be efficient incinerators of hazardous organics. Other organic compounds were measured in both the creosote and the flue gas stream. These compounds, which are not listed in RCRA Appendix VIII, were primarily phenanthrene, anthracene, pyrene, methylnaphthalene, and methyl-pyrene. DRE's of these compounds, which were generally near or slightly below 99.990 percent, are listed in Appendix A, along with POHC's of sites A through K.

Phenol was the primary hazardous compound at site C. Its DRE averaged 99.9996 percent. The boiler at site C was operating at about 25 percent of capacity with very high excess air levels required to maintain superheater

TABLE 68. OTHER VOLATILE ORGANICS DRE RESULTS

Site	Tests	Average CO, ppm	Average NO_x, ppm	Recorded boiler operating conditions	DRE's of volatile POHC's (percent)[a]					
					Carbon tetrachloride	Trichlor-ethylene	Chloro-benzene	Toluene	Benzene	Tetrachlor-ethylene
D	2, 3, and 4	92	211	Unstable burner conditions during test 2. Fluctuation in waste feed rate						99.995- 99.9990 (99.998)
	6, 7	93	165	Steady boiler operation with well mixed waste fuel				99.9990- 99.9993 (99.9991)		
G	1, 2, and 3	107	48	Nominal load and excess air. No boiler operational upsets.	99.992- 99.9995 (99.998)					
K	2	104	158	Nominal load and excess air. No boiler operational upsets.	99.9997- 99.99998 (99.9998)	99.9998- 99.99992 (99.99990)	99.9998- 99.99998 (99.99992)	99.99995- 99.99998 (99.99996)	99.990- 99.998 (99.996)	

[a] Numbers in parentheses represent the test average DRE.

TABLE 69. SEMIVOLATILE ORGANIC DRE'S

Site	Tests	Average CO, ppm	Average NO_x, ppm	Recorded boiler operating conditions	DRE's of volatile POHC's (percent)[a]						
					Phenol	Penta-chlorophenol	Fluorene	Naphthalene	2-4-dimetnyl-phenol	Nitro-benzene	Aniline
A	1, 2, 3, and 4	>500	105	Fluctuating boiler load and emissions resulting from unstable feedrate. Typical of wood-fired stoker.	99.5- 99.993 (99.96)	99.97 99.998 (99.98)	99.98- 99.9998 (99.998)	99.94- 99.995 (99.98)	99.96 99.995 (99.98)		
C	2, 3, and 4	12	40	Low load and high excess air. Stable boiler operation and waste fuel feedrate.	99.998- 99.99990 (99.9996)						
I	2 and 4	120	785	Staged combustion during test 2.						99.99990- 99.99998 (99.99996)	99.9994- 99.9996 (99.9995)

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[a] Numbers in parentheses represent the test average DRE.

steam temperatures. This resulted in an estimated bulk residence time of about 2 sec. which may have counteracted the low furnace temperatures of the low load condition. Site I DRE's for the semivolatile nitrobenzene and aniline were also very high, ranging from 99.99990 to 99.99998 percent for nitrobenzene and from 99.9994 percent to 99.9996 percent for aniline. Staged combustion during test 2 did not result in a reduced DRE for semivolatile organics.

5.2 SUMMARY OF RESULTS AND INTERPRETATION OF TRENDS

Results presented in the preceeding section clearly indicate that industrial boilers tested in these field programs are capable of DRE's exceeding 99.990 percent for POHC's investigated. However, some test results allude to a trend of lower DRE's during non-steady boiler operation characterized by combustion instability and high smoke emissions. It should be reiterated that since the objective of these tests was to measure POHC DRE's under steady boiler operation, selective emission measurements during encountered transient boiler operation and smoke emissions were generally avoided. Therefore, the data base is not sufficient to definitively state that boiler performance in POHC destruction falls below 99.990 percent DRE with high CO resulting from transient and upset operating conditions.

Table 70 summarizes the range in test-averaged DRE for each site and presents both the POHC-specific and total mass-averaged DRE for major volatile organics. On a total mass-weighted average basis, the test boilers with the least demonstrated performance were at site F, followed by sites B, H, and E. The site F boiler was the only test site with a total mass-averaged DRE less than 99.990 (i.e., 99.98 percent destruction) for volatile organics. For the most part, these lower DRE's coincided with unstable burner(s) operation and intermittent high CO and smoke emissions. Similarly, lower DRE results at site E were recorded during tests characterized by fluctuating waste feedrates which when combined with insufficient excess air levels occasionally resulted in smoke and measured CO emissions. Another example of low recorded DRE's with high CO emissions was offered by semivolatile organics measurements made at the site A wood/creosote-fired boiler. The following subsections discuss overall DRE trends with combustion efficiency, POHC concentration in the waste fuel, NO_x, boiler furnace surface heat release rate, and other variables investigated.

5.2.1 Combustion Efficiency

Figures 10 and 11 illustrate the relationship of POHC DRE's as a function of combustion efficiency. Combustion efficiency, based on total carbon utilization, was defined as the percent carbon oxidized to CO_2, that is $[1-CO/CO_2] \times 100$. Figure 10 illustrates the relationship for all calculated DRE's (chlorinated and nonchlorinated POHC's and other major organics) while Figure 11 includes DRE's for chlorinated POHC's only. Also the data are based on the average POHC DRE for each test.

A trend of lower DRE with increased CO emissions is not clearly evident. This is primarily due to three factors. The first is that the bulk of the

TABLE 70. SUMMARY OF TEST AVERAGE DRE'S FOR VOLATILE POHC'S

POHC	Site B	Site D	Site E	Site F	Site G	Site H	Site I	Site J	Site K	Range	Weighted average
Carbon tetrachloride			99.9990- 99.9998 (99.9996)	99.98- 99.9990 (99.995)	99.995- 99.9990 (99.998)	99.97- 99.9994 (99.98)	99.9990- 99.9993 (99.9993)	99.997- 99.9998 (99.9990)	99.9998	99.97- 99.9998	99.9992
Trichloroethylene			99.994- 99.9995 (99.998)	99.98 99.998 (99.996)			99.99990- 99.99992 (99.99991)	99.998- 99.99993 (99.9996)	99.99990	99.98- 99.99993	99.9994
1,1,1-Trichloroethane						99.97- 99.9996 (99.994)				99.97- 99.9996	99.994
Chlorobenzene			99.995- 99.99990 (99.998)	99.96- 99.992 (99.98)		99.990- 99.997 (99.992)	99.997- 99.9990 (99.998)	99.8- 99.97 (99.95)	99.99992	99.8 99.99992	99.992
Benzene							99.97- 99.98 (99.97)		99.996	99.97- 99.996	99.990
Toluene	99.991	99.9992- 99.99990 (99.9996)	99.997	99.90- 99.97 (99.95)			99.998	99.9990- 99.9997 (99.9990)	99.99996	99.90- 99.99996	99.998
Tetrachloroethylene		99.994- 99.9992 (99.998)								99.994- 99.9992	99.998
Methylmethacrylate			99.95- 99.997 (99.991)							99.95- 99.995	99.991
Mass-weighted average	99.991	99.994- 99.99990 (99.998)	99.95- 99.99990 (99.995)	99.90- 99.9990 (99.98)	99.995- 99.9990 (99.998)	99.97- 99.9996 (99.991)	99.97- 99.99992 (99.998)	99.8- 99.99993 (99.9990)	99.996- 99.99996 (99.9997)	99.8- 99.99996	99.998

[a] Numbers in parentheses represent the site-average DRE for the POHC.

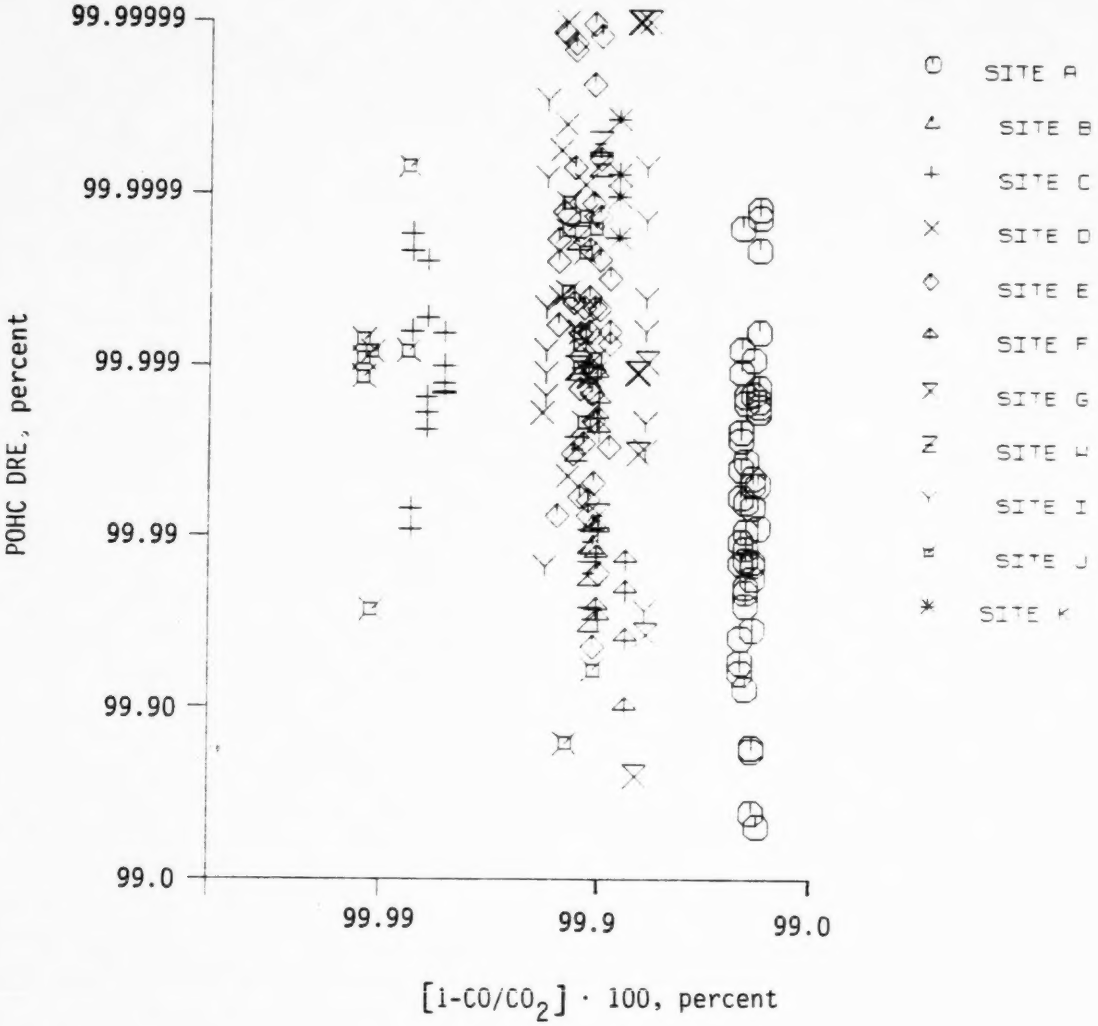

Figure 10. Effect of combustion efficiency on test average POHC DRE.

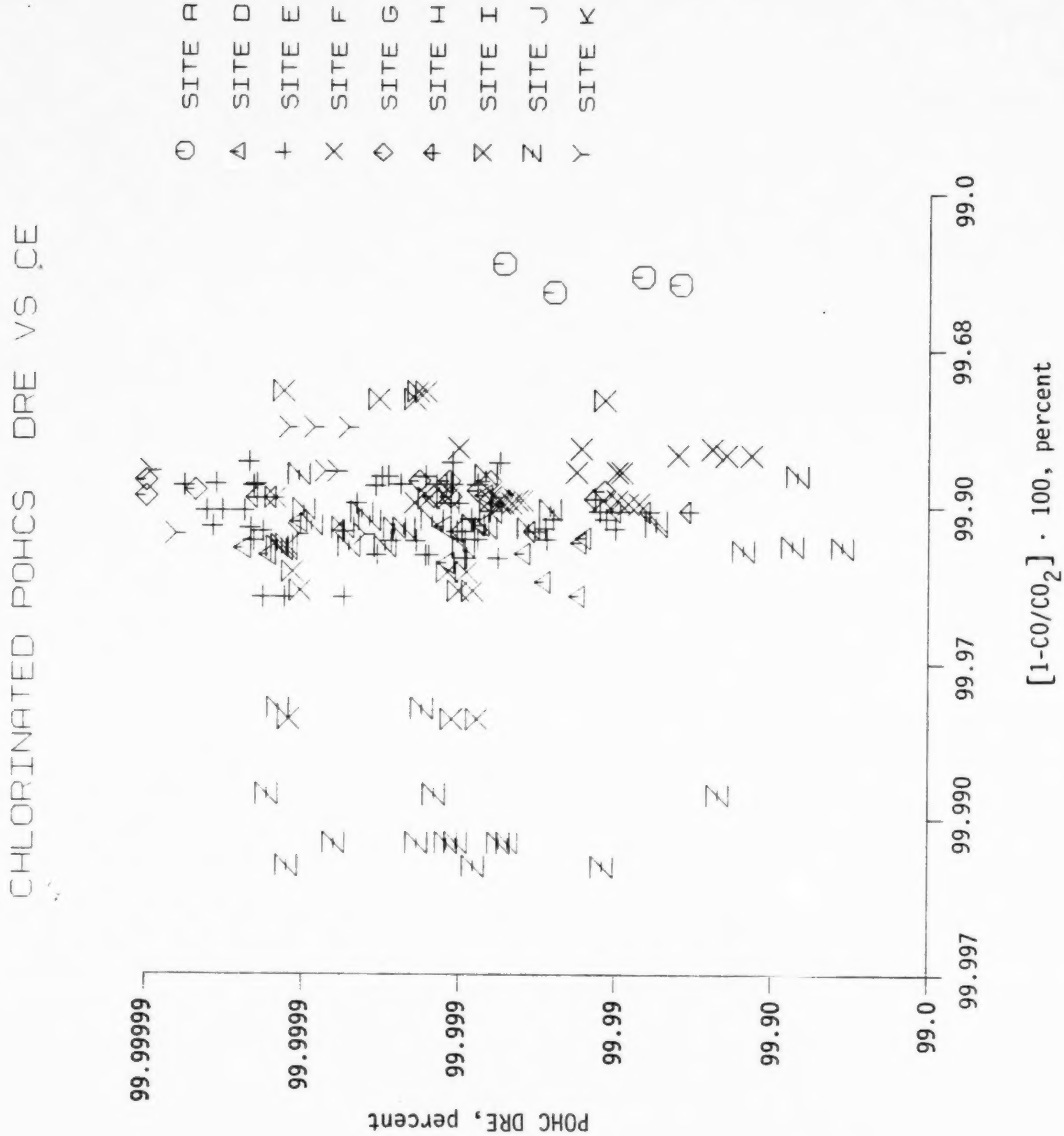

Figure 11. Effect of combustion efficiency on chlorinated POHC DRE.

DRE data was obtained when CO emissions were in the range of about 70 to 140 ppm, generally corresponding to [1 -CO/CO_2] x 100 of about 99.94 to 99.84. The second factor is the site J chlorobenzene results. These DRE results were based for the most part on the detection limit of flue gas samples and not on actual measured concentrations. Therefore, actual DRE's for site J chlorobenzene most likely were greater than those shown in Figures 10 and 11. The third factor is suspect CO emissions for site F. Instrument malfunction during a portion of this field test program probably resulted in erroneously low CO emissions. When these factors are considered, the data may suggest a general trend of lower DRE with decreasing carbon utilization (higher CO emissions). This trend is aided by the site A results, which showed low DRE's of semivolatile chlorinated POHC's during CO values greater than 500 ppm. A tentative conclusion may be that DRE of 99.99 percent or greater is most likely to occur with CO less than 80 to 100 ppm. Although the validity of CO as a surrogate for low DRE remains speculative at this time, the effect of transient boiler operation and high CO emissions on DRE should be investigated in greater detail.

5.2.2 POHC Concentration in the Waste

Figure 12 illustrates the relationship of POHC DRE with POHC concentration in the waste fuel. POHC concentration is normalized by the ratio of the waste heat input to the total heat input. Although DRE's for any given POHC concentration can vary by as much as four orders of magnitude, there seems to be a general trend of high DRE with higher POHC concentration. This suggests that the amount of POHC breakthrough is independent of the POHC concentration in the waste fuel.

There are several factors that could enter in this apparent trend. With the exception of site A, high DRE's were generally measured for semivolatile organics. These semivolatile POHC's incinerated in boilers designed for gas and oil fuels were generally present in high-waste fuel concentrations. This is the case for phenol, bis(2-chloroethyl)ether, epichlorohydrin, bis(2-chloroisopropyl)ether, nitrobenzene, aniline, and other semivolatile organics not listed in RCRA Appendix VIII for sites C, D, E, G, and I. Another factor is the amount of background contamination of sampling and analytical techniques which tends to be more significant with low level emissions resulting from low POHC firing rates. Yet another factor may be associated with the amount of PIC's generated by combustion of fossil fuels, primarily fuel oils, coal and wood. At low POHC flue gas concentrations, these PIC's would tend to play a greater role in the estimation of POHC DRE.

5.2.3 NO_x Emissions

It was hypothesized that NO_x emissions may act as indicators for the efficiency of POHC destruction. This was based on the concept that high temperature, long residence time and turbulent mixing, which are conducive to high thermal NO formation, are also desirable for efficient POHC destruction. Therefore, the higher the thermal NO the higher is the anticipated DRE. However, a comparison of DRE's with NO_x between boilers burning different fuels can be misleading because the total NO_x generated is both a function of

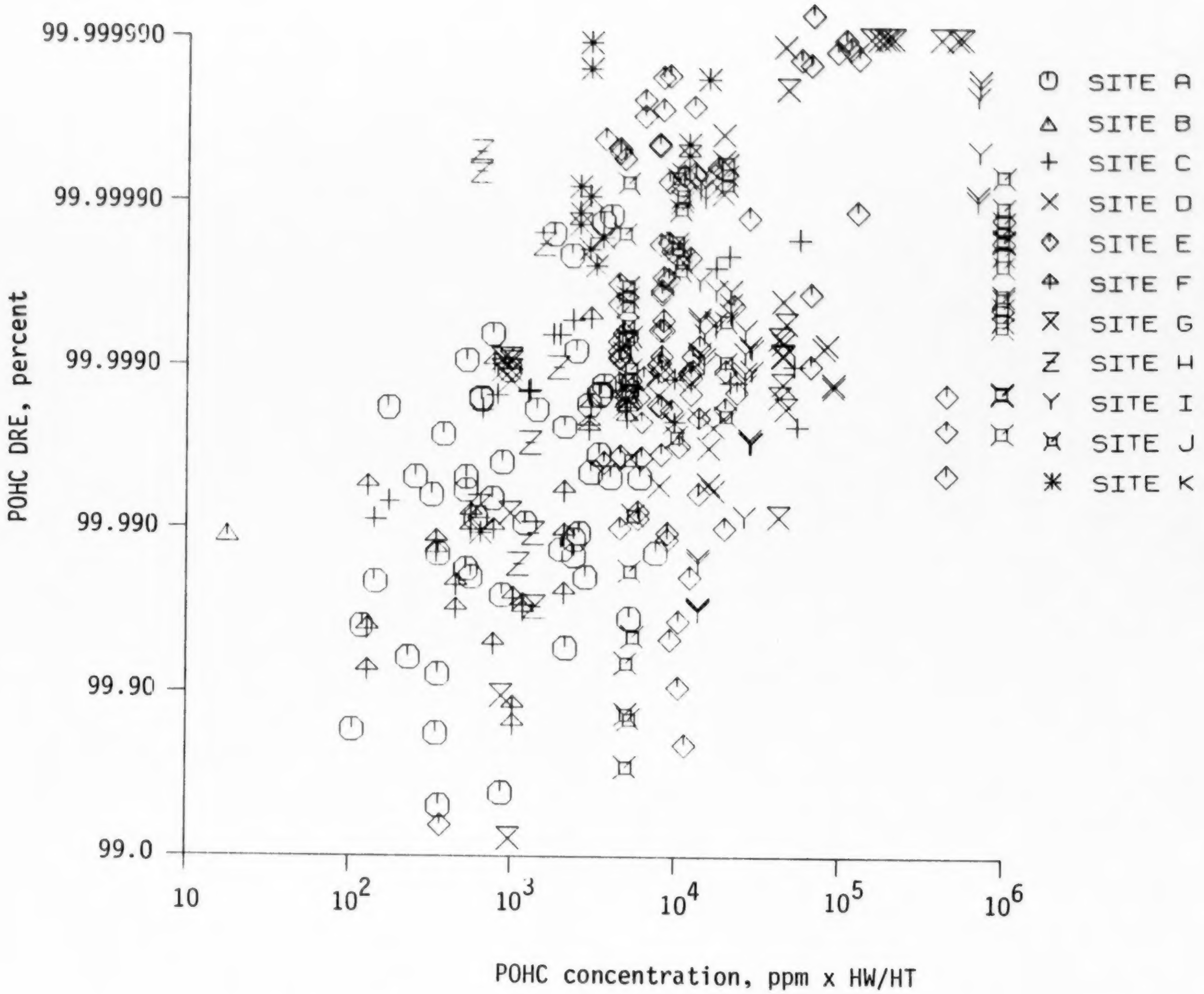

Figure 12. Effect of POHC concentration on DRE.

fuel NO and thermal NO. With heavy oils, coal, or nitrated organic waste, the fuel NO contribution predominates.

Figure 13 illustrates the relationship of DRE's with measured NO_x emissions. The data seem to suggest a general trend of higher DRE's with higher NO_x emissions. This trend is more clearly visible in Figure 14 which summarizes only the DRE's of chlorinated POHC's. In fact, chlorinated POHC DRE's tend to be above an imaginary line, which indicates 100 percent DRE's of >99.990 percent for NO_x >250 ppm and nearly 100 percent DRE's of >99.9990 for NO_x >400 ppm. Again, this trend can be misleading because several boilers burned high nitrogen fuels while others burned natural gas as the primary fuel. Figure 15 shows the mass average DRE's for each site. The trend indicated by the lower limit of the test average DRE's is no longer visible since high DRE's also occurred over the range of NO_x values.

The site I boiler was operated under unstaged and staged combustion air. Under unstaged conditions, the NO_x were very high due to high levels of nitrated organics (nitrobenzene and aniline). Although the staged combustion resulted in a significant reduction in NO_x, the DRE's did not change appreciably. However, this NO_x reduction was primarily due to suppression of fuel NO; therefore, the overall thermal environment of the furnace may have not changed significantly.

5.2.4 Surface Heat Release Rate

Surface heat release rates of industrial boiler test sites were calculated based on the total heat input divided by the waterwall surface of the firebox. Surface heat release rates provide some measure of the thermal profile in the firebox. Actual bulk gas temperature profiles depend heavily on the radiant properties of the combustion products.

Figure 16 illustrates the relationship of DRE versus surface heat release rate calculated for individual tests. With the exception of a few outliers the trend seems to be similar to that shown for DRE versus NO_x. That is, generally higher DRE's may be likely with higher surface heat release rates. Therefore, firetube boilers, which typically have higher surface heat release rates than watertubes, may actually be as effective or more effective than larger watertube units. Chlorobenzene destruction in the boiler at site J and propionaldehyde at site G were the only exceptions, showing low DRE's with relatively high surface heat release rates. It should be recalled that chlorobenzene results for site J were generally questionable due to poor detection limits. Also propionaldehyde was not well quantified at site G. Figure 17 also shows a trend of increasing DRE with surface heat release rate for site average DRE's. DRE results for sites A, B, F, and H fall below the trend indicated by other test sites. However, as discussed in Section 2, boiler operation at sites A, B, and F was generally characterized by unstable combustion conditions. Low DRE results at site H may be due to high organics generated from combustion of coal and low waste fuel ratio.

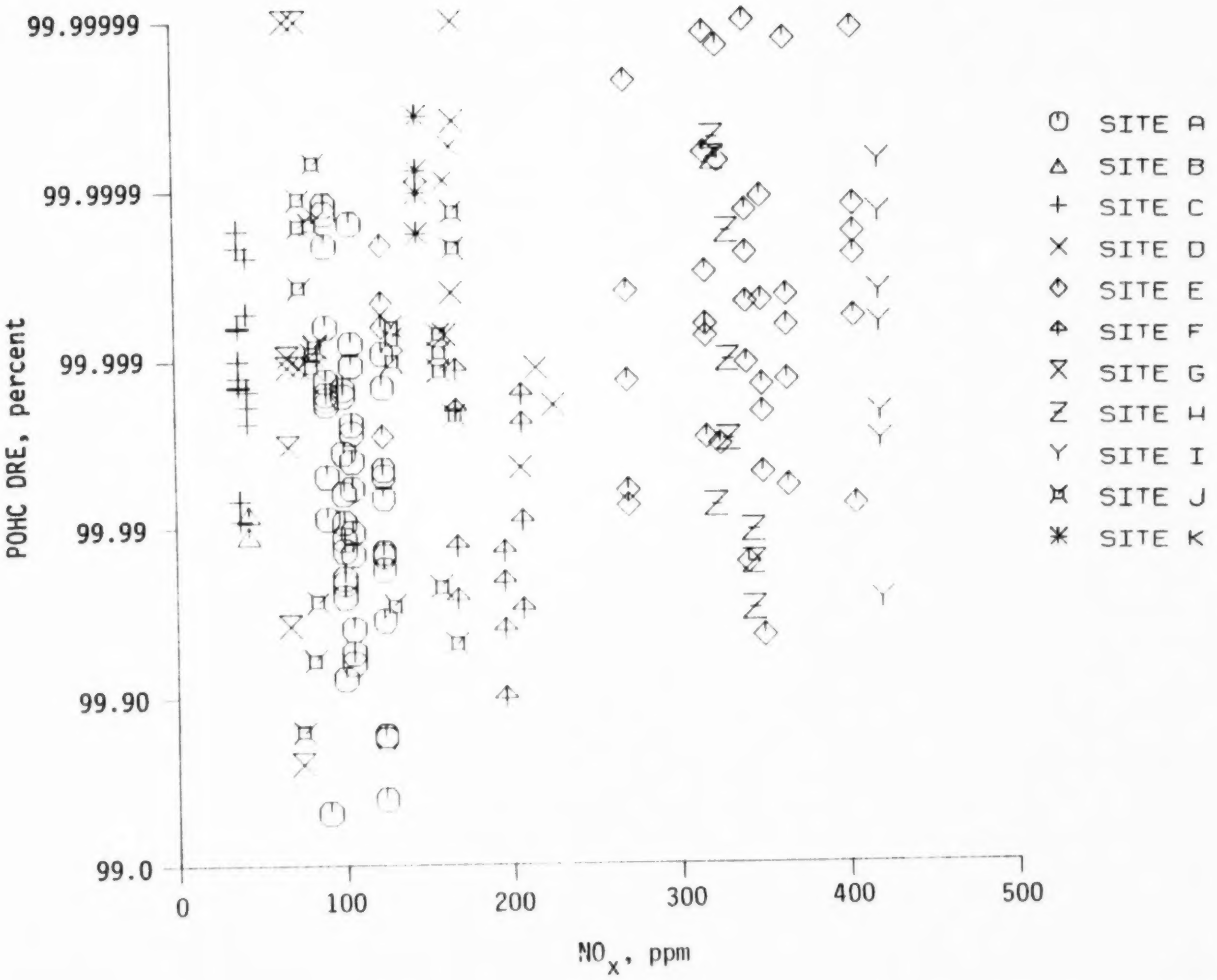

Figure 13. DRE trends with NO_x emissions -- test averaged DRE's.

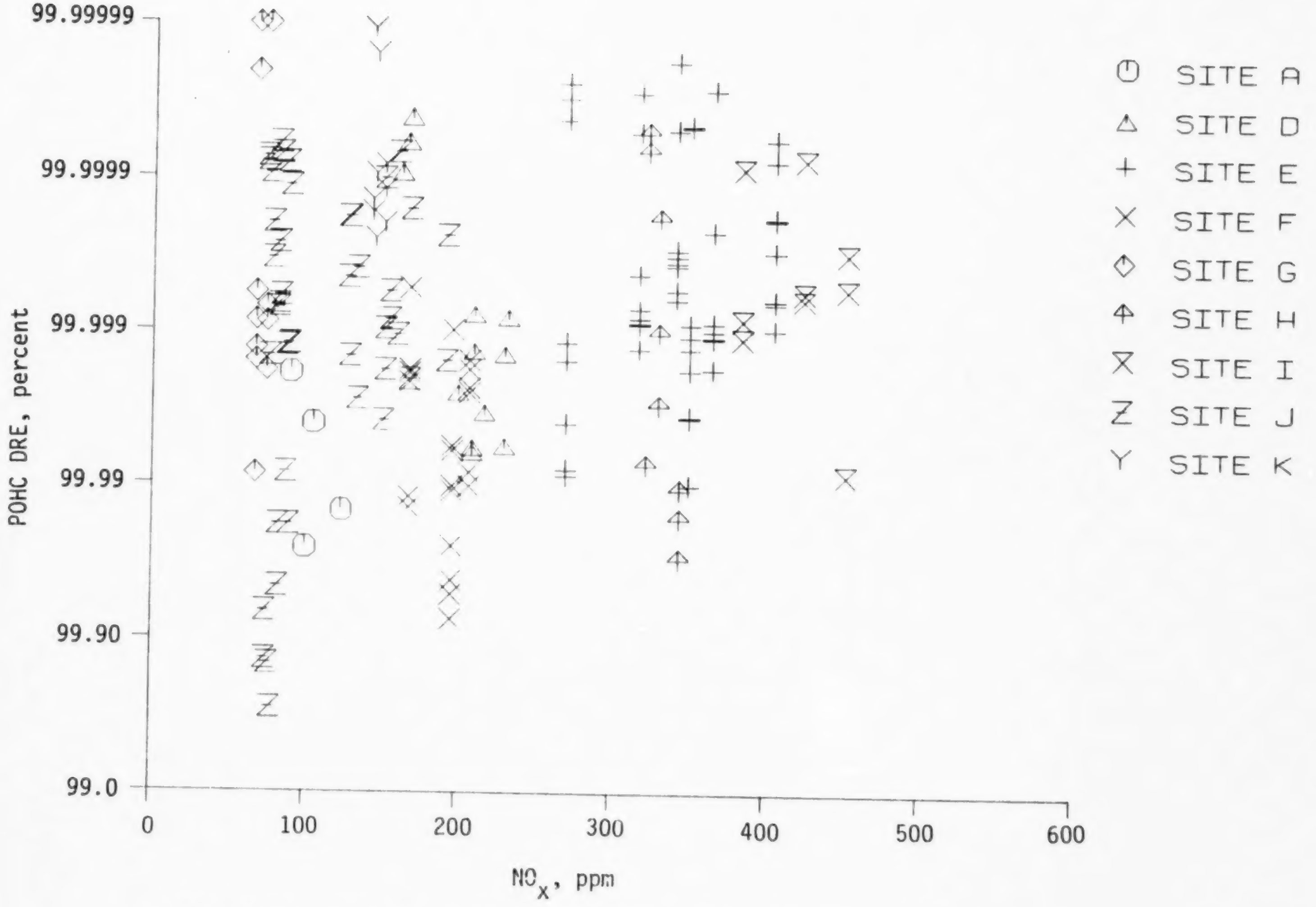

Figure 14. DRE trends of chlorinated POHC's with NO$_x$ emissions

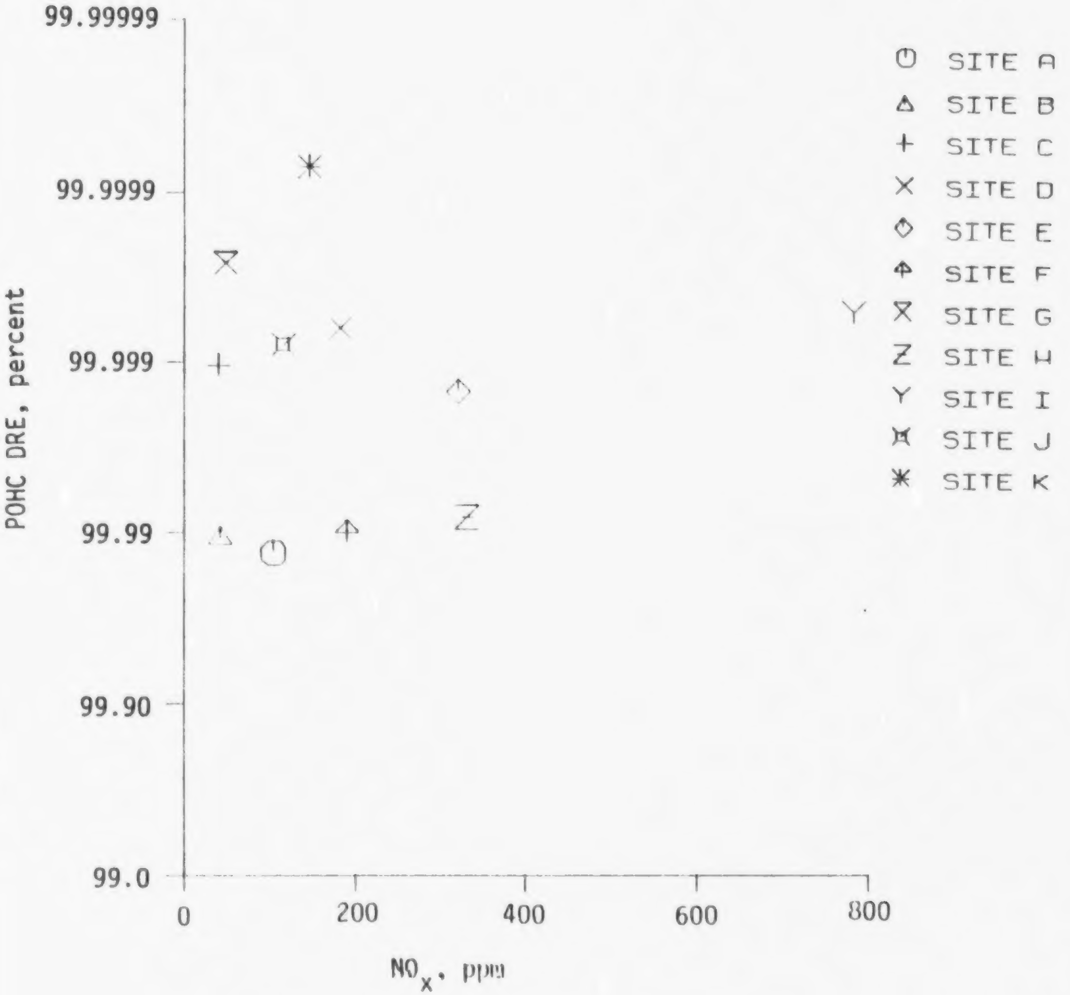

Figure 15. DRE trends with NO_x emissions -- site average DRE's.

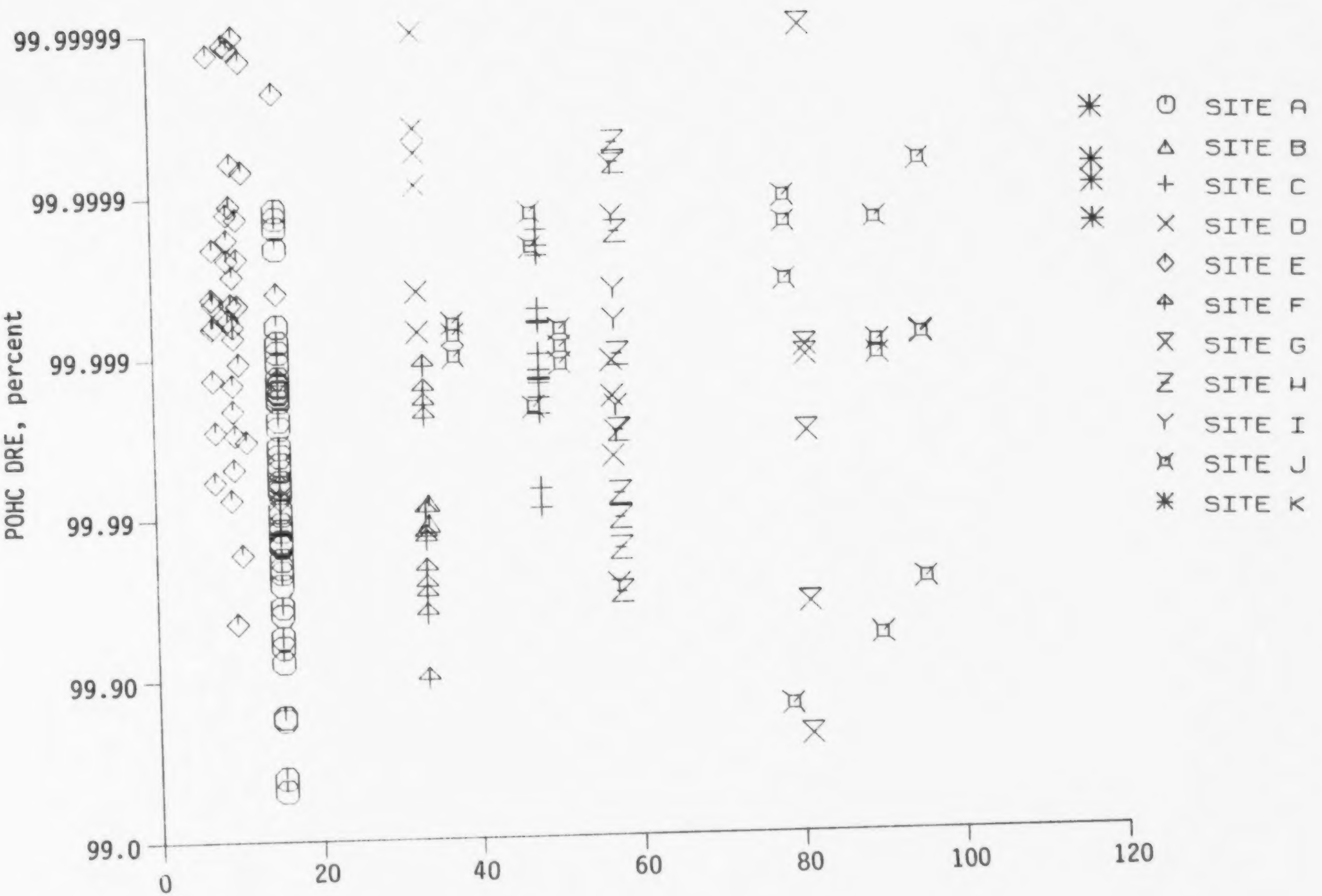

Figure 16. Effect of surface heat release rate on DRE -- test average data.

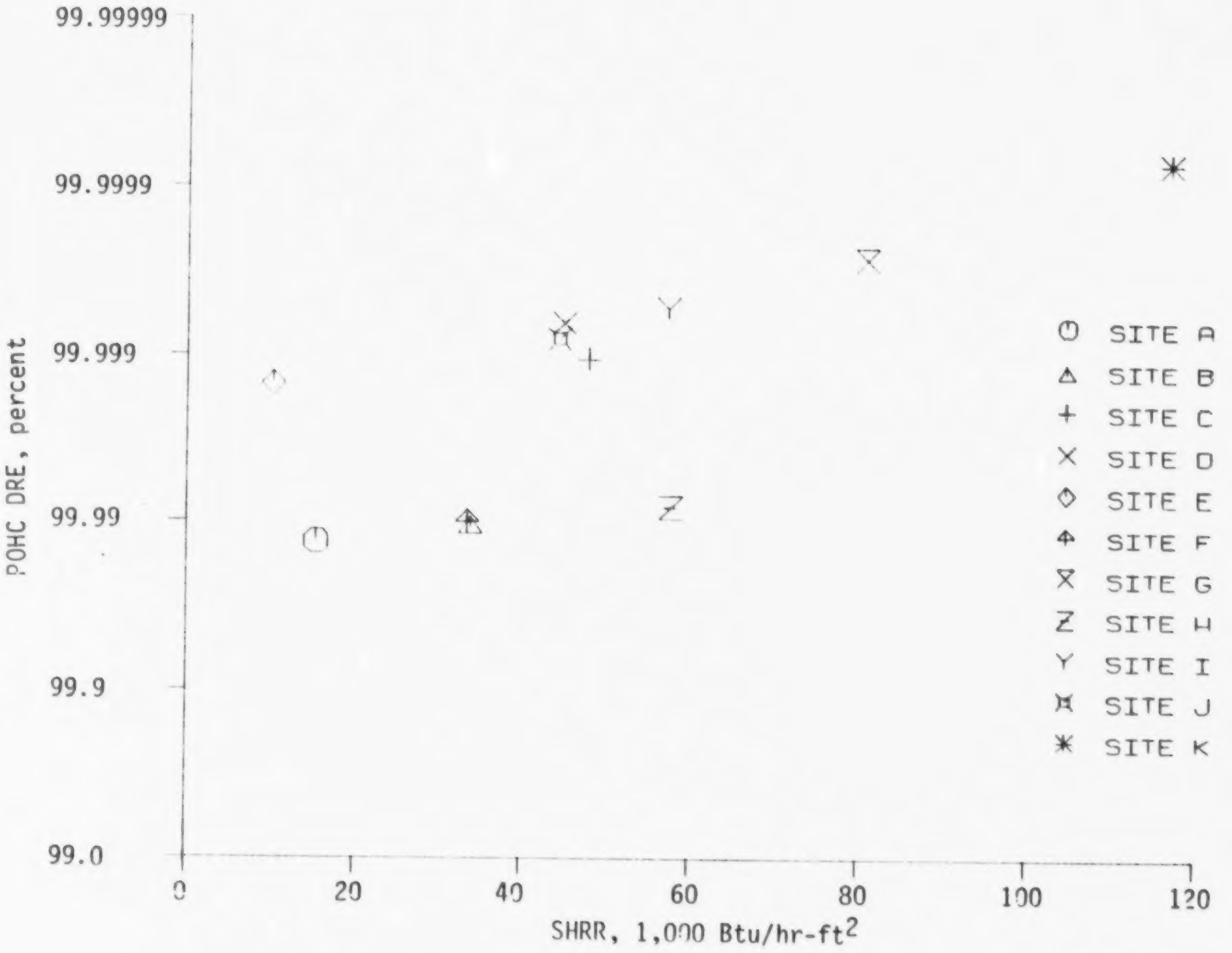

Figure 17. Effect of surface heat release rate on DRE -- site average data.

SECTION 6

CONCLUSIONS

Organic emission measurements were performed at 11 industrial test sites where hazardous organic wastes were cofired in boilers for disposal and energy recovery. The industrial boilers tested comprise a broad range of steam generator designs with capacities of 1.1 to 32 kg/s (8,500 to 250,000 lb/hr). A total of 42 tests were performed with the boilers firing hazardous waste fuels as a supplement to fossil fuel (cofire) or supplying all the thermal energy to these boilers. Each test generally included three separate measurements of volatile organic emissions for a total number of about 120 individual measurements. Test results focused on quantitation of the thermal destruction (DRE) of hazardous organics (POHC's) and the formation of products of incomplete combustion (PIC's). POHC's of interest were the volatile compounds: carbon tetrachloride, chlorobenzene, trichloroethylene, toluene, benzene, tetrachlorethylene, and methylmethacrylate. Other compounds of interest were the semivolatile organics: phenol, pentachlorophenol, bis(2-chloroethyl)ether, bis(2-chloroisopropyl)ether, nitrobenzene, aniline, naphthalene, fluorene, and 2-4 dimethylphenol. Firing and emission rates of other major organic compounds were also measured to determine DRE.

Test results indicate that industrial boilers operating under typical industrial practice of heat input, waste/fuel ratio, and excess air can achieve DRE's of individual POHC's in excess of four nines (99.99 percent destruction). Measured DRE's ranged from about 99.90 to 99.99996 percent. Investigation of site-specific test data and corresponding boiler operating conditions has revealed several possible trends in DRE and PIC formation. Although these trends cannot be stated with absolute certainty, they are summarized here to suggest areas of further research.

6.1 EFFECTS OF COMBUSTION EFFICIENCY ON DRE

There is suggestive evidence that the DRE of POHC's may be greatly reduced during boiler operation conducive to soot formation and high CO and smoke emission. Test results at three sites (A, E, and F) provide the most supportive evidence. Soot formation with high CO and smoke emissions can be the result of several transient boiler operations or the cause of improper burner settings. Ineffective fuel/air mixing at the site A wood stoker accompanied by combustion cooling through high excess air levels resulted in high CO and DRE's generally below 99.990 percent. Waste fuel flow surges, fuel jets interference, and insufficient excess air resulted in less than

99.990 percent DRE for some POHC's at site E. Improper fuel gun position in the burner throat, probable jet impingement on waterwalls and ineffective atomization through burner tip coking resulted in consistently low DRE for all POHC's at site F.

However, the data does not clearly support the concept of CO or hydrocarbon emissions as a surrogate for POHC DRE determination. One possible explanation is that CO emissions can be manifested through several mechanisms depending on boiler type and fuel. Operating conditions which can lead to higher combustible emissions may result in no measurable change in POHC DRE if the mechanism does not have a similar effect on individual POHC's as it does on the primary fuel. For example, sufficiently low excess air will result in CO emissions followed by smoke for oil-fired burners. However, both temperature and residence time are not significantly reduced so that POHC DRE can remain high. Kinetics data based on pyrolytic destruction of several POHC's suggests that both temperature and time in industrial boiler furnaces are sufficiently high to permit near complete destruction by pyrolysis alone.

Therefore, future studies should concentrate not only on the effect of CO emissions on DRE, but, also on the mechanisms by which these emissions occur. The data available through these test programs were generally insufficient to provide clear evidence of the impact of boiler transients and upsets on POHC DRE's.

6.2 EFFECT OF WASTE FUEL POHC CONCENTRATION ON DRE

The data also tends to suggest a trend of higher DRE's with increasing POHC concentration in the waste fuel. Site average DRE's of greater than 99.990 percent were found to be more likely for a waste fuel POHC concentration of greater than 3,000 ppm corrected for the waste-to-total fuel heat input ratio. This result may be attributed to two major factors. The first is the amount of background contamination or sampling and analytical errors associated with low level detection of volatile organics. This background contamination of sampling/analytical errors plays a greater role in DRE calculations for low feedrate organics. An implication of this factor is that POHC concentration in waste fuels should be greater than 3,000 ppm times the ratio of total heat to waste heat inputs to eliminate misinterpretation of low DRE results. A second factor is associated with the amount of PIC's generated by combustion of fossil fuels, primarily fuel oils, coal and wood. Evidence of PIC organic emissions during baseline testing suggests that the contribution of PIC's to the total POHC breakthrough during cofiring can be significant. The implication of this factor is that POHC's for DRE testing should be carefully selected to avoid the bias of PIC formation.

6.3 EFFECT OF NO_x AND SURFACE HEAT RELEASE ON DRE

NO_x emissions and furnace waterwall surface heat release rates were two parameters that were correlated with DRE. Both NO_x formation (through thermal NO) and surface heat release rates can be indicators of the thermal environment in the flame and throughout the furnace. Interestingly, both parameters showed similar trends; that is, higher NO_x and surface heat release rates generally resulted in higher measured DRE's. Less than 99.990 percent DRE's were found to generally correspond to NO_x gas concentration of less than 250 ppm and surface heat release rates less than 180 kW/m^2 (60,000 $Btu/hr\text{-}ft^2$). The higher the NO_x and surface heat release rates, the higher the range in measured POHC DRE. These trends would indicate that lower boiler loads may be more likely to result in lower DRE's and that the temperature dependence of POHC destruction is more significant than furnace residence time. This conclusion is not meant to indicate a definite relationship but rather a potential trend that warrants further investigation.

6.4 PIC EMISSIONS

The test data on PIC emissions is not as extensive as POHC DRE data. However, the following conclusions can be drawn.

Baseline (fossil fuel only) tests indicate that volatile organics, both chlorinated and nonchlorinated, are formed as the result of fossil fuel combustion. These emissions which included most of the POHC's under investigation may have a measurable impact on the total POHC's measured under cofiring conditions. Volatile PIC emissions included several chlorinated organics such as chloromethane, chloroform, methylene chloride, tetrachloroethylene, trichloroethane, dichloroethane, and dichloropropylene, as well as nonchlorinated organics such as toluene and benzene. Total PIC emissions were about one order of magnitude or greater than total POHC's breakthrough. Chloromethane, methylene chloride, and chloroform accounted for more than 75 percent of the total chlorinated PIC's. Toluene contributed the bulk of total nonchlorinated PIC's. A general trend of lower PIC emissions with greater POHC DRE's was identified from the available test data. This suggests that combustion conditions leading to more efficient POHC destruction are also likely to result in lower PIC formation. This conclusion can also be interpreted as meaning that lower PIC contribution by fossil fuel combustion is likely to result in a measurable effect on POHC DRE.

6.5 SOLID AND LIQUID WASTE STREAMS

Organic analyses of liquid and solid discharge streams from industrial boilers indicated that these contain a relatively minor quantity of hazardous organic compounds compared to flue gas streams. Combined with respective discharge rates, flue gas constitutes the major POHC and PIC discharge stream.

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APPENDIX A

DATA LISTING

The following table summarizes the available data base compiled from emission testing at sites A through K. The following provides an explanation of the separate sets of data entries:

- STR -- Code describing the site (S), test (T), and run (R) number for each emission data set. Site numbers range from 1 to 11 corresponding to the alphabetical site identification A through K. Test number corresponds to the individual tests performed at each site. Generally test 1 represents the baseline test with the exception of sites A (1), G (7), and J (10) for which no baseline tests were performed. Run number corresponds to the individual sample measurements taken. Generally for volatile POHC's three separate measurements were taken for each test. For semivolatile POHC's only one measurement per test was made. A zero entry for run number corresponds to the average results for a given test.

- ID -- The identification code corresponds to a specific organic compound:

  1 -- Phenol

  2 -- 2,4-dimethylphenol (for site A only)

  3 -- 2,6-dinitrotoluene (for site A only)

  4 -- Naphthalene (for site A only)

  5 -- Fluorene (for site A only)

  6 -- Pentachlorophenol (for site A only)

  7 -- Phenanthrene (for site A only)

  8 -- Anthracene (for site A only)

  9 -- Pyrene (for site A only)

10 -- Methylnaphthalene (for site A only)

11 -- Biphenyl (for site A only)

12 -- Dibenzofuran (for site A only)

13 -- Methylpyrene (for site A only)

14 -- Chrysene (for site A only)

15 -- Bis(2-chloroisopropyl)ether (for site G only)

16 -- Epichlorohydrin (for site G only)

18 -- Toluene

19 -- Xylenes (for site B only)

21 -- C_3 Alkyl-benzene (for site C only)

22 -- Benzene acetaldehyde (for site C only)

23 -- 2,2'Methylene bisphenol (for site C only)

24 -- 2,4'Methylene bisphenol (for site C only)

25 -- Tetrachloroethylene (for site D only)

26 -- Bis(2-chloroethyl)ether (for site D only)

27 -- Methylmethacrylate (for site E only)

28 -- α-hydroxy methyl isobutyrate (for site E only)

29 -- α-hydroxy methyl isobutyrate methyl ether (for site E only)

30 -- Carbon tetrachloride

31 -- Chlorobenzene

32 -- Trichloroethylene

33 -- Benzene

34 -- Nitrobenzene (for site K only)

35 -- Aniline (for site K only)

36 -- Propionaldehyde (for site G only)

37 -- 1,1,1-Trichloroethane (for site H only)

- O_2 -- Average excess oxygen concentration in the flue gas, percent dry basis
- CO_2 -- Average CO_2 concentration in the flue gas, percent dry basis
- CO -- CO flue gas concentration, ppm dry as measured. Generally test average CO is reported except for sites E (5), F (6), I (9), J (10), and K (11) where run averages are reported.
- NO_x -- NO_x flue gas concentration, ppm dry as measured. Test average is reported except for sites I (9), J (10), and K (11) where run averages are reported.
- TUHC -- TUHC flue gas concentration, ppm dry as measured. No values were obtained for sites C (3), D (4), E (5), and K (11).
- W/T -- Ratio of heat input from waste fuel to the total heat input to the boiler
- PPM IN -- Concentration of POHC in the waste fuel, parts per million by weight
- INPUT -- POHC feedrate to the boiler, micrograms per second
- OUT -- POHC emission rate measured in the flue gas, micrograms per second
- DRE -- The destruction and removal efficiency of the POHC, (1-out/input) x 100
- CE -- The logarithm of the ratio of CO emission to CO_2 concentration in the stack flue gas

Note: Low DRE's for chlorobenzene for site J, tests 1, 3, and 5 are due to high detection limits. These data were excluded from the figures.

STR	ID	O2	CO2	CO	NOX	TUHC	W/T	PPM IN	INPUT	OUT	DRE	CE
110	1	11.0	10.1	600	90	20.0	0.400	900	44700	220.0	99.50784	-2.23
120	1	10.4	10.1	550	124	0.0	0.400	1300	65000	3.2	99.99508	-2.26
130	1	10.4	9.5	490	100	0.0	0.400	800	40000	2.5	99.99374	-2.29
140	1	10.5	9.7	470	105	0.0	0.400	580	29000	18.0	99.93793	-2.31
110	2	11.0	10.1	600	90	20.0	0.400	650	65000	3.2	99.99508	-2.23
120	2	10.4	10.1	550	124	0.0	0.400	1300	18000	3.2	99.98222	-2.26
130	2	10.4	9.5	490	100	0.0	0.400	360	15000	3.2	99.97867	-2.29
140	2	10.5	9.7	470	105	0.0	0.400	300	33000	13.0	99.96061	-2.31
110	3	11.0	10.1	600	90	20.0	0.400	430	33000	0.6	99.99818	-2.23
120	3	10.4	10.1	550	124	0.0	0.400	1300	65000	0.6	99.99908	-2.26
110	4	11.0	10.1	600	90	20.0	0.400	10000	507000	25.0	99.99507	-2.23
120	4	10.4	10.1	550	124	0.0	0.400	19000	950000	133.0	99.98600	-2.26
130	4	10.4	9.5	490	100	0.0	0.400	6000	300000	35.0	99.98833	-2.29
140	4	10.5	9.7	470	105	0.0	0.400	5400	270000	146.0	99.94593	-2.31
110	5	11.0	10.1	600	90	20.0	0.400	5700	283000	0.6	99.99979	-2.23
120	5	10.4	10.1	550	124	0.0	0.400	7600	220000	10.0	99.99545	-2.26
130	5	10.4	9.5	490	100	0.0	0.400	5000	250000	34.0	99.98640	-2.29
140	5	10.5	9.7	470	105	0.0	0.400	4400	380000	0.6	99.99985	-2.31
110	6	11.0	10.1	600	90	20.0	0.400	3500	173000	3.2	99.99815	-2.23
120	6	10.4	10.1	550	124	0.0	0.400	6000	300000	44.0	99.98533	-2.26
130	6	10.4	9.5	490	100	0.0	0.400	2200	110000	28.0	99.97454	-2.29
140	6	10.5	9.7	470	105	0.0	0.400	2200	110000	4.4	99.99600	-2.31
110	7	11.0	10.1	600	90	20.0	0.400	8800	440000	0.6	99.99986	-2.23
120	7	10.4	10.1	550	124	0.0	0.400	13000	650000	228.0	99.96492	-2.26
130	7	10.4	9.5	490	100	0.0	0.400	7000	350000	70.0	99.98000	-2.29
140	7	10.5	9.7	470	105	0.0	0.400	6400	320000	34.0	99.98937	-2.31
110	8	11.0	10.1	600	90	20.0	0.400	1900	94000	0.6	99.99936	-2.23
120	8	10.4	10.1	550	124	0.0	0.400	260	13000	22.0	99.83077	-2.26
130	8	10.4	9.5	490	100	0.0	0.400	3000	150000	14.0	99.99067	-2.29
140	8	10.5	9.7	470	105	0.0	0.400	2400	120000	1.3	99.99892	-2.31
110	9	11.0	10.1	600	90	20.0	0.400	9900	493000	0.6	99.99988	-2.23
120	9	10.4	10.1	550	124	0.0	0.400	15000	750000	37.0	99.99506	-2.26
130	9	10.4	9.5	490	100	0.0	0.400	8400	420000	15.0	99.99643	-2.29
140	9	10.5	9.7	470	105	0.0	0.400	6200	310000	2.5	99.99920	-2.31
110	10	11.0	10.1	600	90	20.0	0.400	1600	82000	1.3	99.99841	-2.23
120	10	10.4	10.1	550	124	0.0	0.400	2200	11000	45.0	99.59091	-2.26

STR	ID	O2	CO2	CO	NOX	TUHC	W/T	PPM IN	INPUT	OUT	DRE	CE
130	10	10.4	9.5	490	100	0.0	0.400	1400	70000	14.0	99.98000	-2.29
140	10	10.5	9.7	470	105	0.0	0.400	1300	65000	3.8	99.99416	-2.31
110	11	11.0	10.1	600	90	20.0	0.400	7400	370000	6.4	99.99827	-2.23
120	11	10.4	10.1	550	124	0.0	0.400	8600	430000	6.3	99.99854	-2.26
130	11	10.4	9.5	490	100	0.0	0.400	8400	420000	6.3	99.99850	-2.29
140	11	10.5	9.7	470	105	0.0	0.400	5200	260000	6.3	99.99757	-2.31
110	12	11.0	10.1	600	90	20.0	0.400	9000	45000	0.6	99.99866	-2.23
120	12	10.4	10.1	550	124	0.0	0.400	860	43000	76.0	99.82326	-2.26
130	12	10.4	9.5	490	100	0.0	0.400	880	44000	34.0	99.92273	-2.29
140	12	10.5	9.7	470	105	0.0	0.400	960	48000	1.3	99.99729	-2.31
110	13	11.0	10.1	600	90	20.0	0.400	1500	73000	6.4	99.99123	-2.23
120	13	10.4	10.1	550	124	0.0	0.400	1900	95000	6.3	99.99336	-2.26
130	13	10.4	9.5	490	100	0.0	0.400	1600	80000	1.3	99.99837	-2.29
140	13	10.5	9.7	470	105	0.0	0.400	880	44000	6.3	99.98568	-2.31
140	14	10.5	9.7	470	105	0.0	0.400	2400	120000	1.3	99.99892	-2.31
240	18	5.3	9.7	59	46	57.0	0.010	550	18400	1.6	99.99130	-3.22
200	19	5.3	9.7	59	46	57.0	0.010	1770	44500	4.7	99.98944	-3.22
320	1	9.7	7.6	15	38	0.0	0.380	56000	15000000	190.0	99.99873	-3.70
330	1	10.5	7.3	12	43	0.0	0.370	47000	12000000	30.0	99.99975	-3.78
340	1	10.7	7.1	10	38	0.0	0.390	53000	13000000	28.0	99.99979	-3.85
320	21	9.7	7.6	15	38	0.0	0.380	138000	37000000	370.0	99.99900	-3.70
330	21	10.5	7.3	12	43	0.0	0.370	150000	37000000	880.0	99.99762	-3.78
340	21	10.7	7.1	10	38	0.0	0.390	145000	36000000	61.0	99.99983	-3.85
320	22	9.7	7.6	15	38	0.0	0.380	4700	1300000	8.4	99.99936	-3.70
330	22	10.5	7.3	12	43	0.0	0.370	6400	1600000	8.4	99.99947	-3.78
340	22	10.7	7.1	10	38	0.0	0.390	5000	1300000	8.3	99.99936	-3.85
320	23	9.7	7.6	15	38	0.0	0.380	3300	890000	13.0	99.99854	-3.70
330	23	10.5	7.3	12	43	0.0	0.370	1800	450000	8.4	99.99813	-3.78
340	23	10.7	7.1	10	38	0.0	0.390	460	120000	8.3	99.99309	-3.85
320	24	9.7	7.6	15	38	0.0	0.380	3400	920000	13.0	99.99859	-3.70
330	24	10.5	7.3	12	43	0.0	0.370	2200	550000	8.4	99.99847	-3.78
340	24	10.7	7.1	10	38	0.0	0.390	370	93000	8.3	99.99107	-3.85
421	25	5.1	12.2	105	210	0.0	0.300	280000	76700000	570.0	99.99925	-3.07
422	25	5.1	12.1	105	210	0.0	0.300	301000	78500000	1010.0	99.99871	-3.06
423	25	5.3	11.8	128	230	0.0	0.300	301000	78500000	1070.0	99.99863	-2.96
420	25	5.2	12.0	112	216	0.0	0.300	294000	77900000	883.3	99.99887	-3.03
431	25	4.8	12.2	80	232	0.0	0.290	271000	69300000	540.0	99.99922	-3.18
432	25	5.5	12.5	72	217	0.0	0.290	54200	15700000	510.0	99.99675	-3.24

STR	ID	O2	CO2	CO	NOX	TUHC	W/T	PPM IN	INPUT	OUT	DRE	CE
433	25	5.6	13.5	70	230	0.0	0.290	54200	15700000	850.0	99.99459	-3.29
430	25	5.3	12.7	74	226	0.0	0.290	126466	33566668	633.3	99.99811	-3.24
441	25	5.4	12.4	95	209	0.0	0.180	44500	11700000	640.0	99.99453	-3.12
442	25	5.4	12.0	95	209	0.0	0.180	94700	23500000	1370.0	99.99417	-3.10
443	25	5.1	13.1	93	200	0.0	0.180	94700	23500000	560.0	99.99762	-3.15
440	25	5.3	12.5	94	206	0.0	0 180	77966	19566666	856.7	99.99562	-3.12
450	26	6.0	12.2	89	168	0.0	0.470	41000	7690000	3.0	99.99996	-3.14
460	26	6.2	11.8	82	166	0.0	0.470	40200	7530000	4.2	99.99995	-3.16
470	26	5.9	12.1	107	162	0.0	0.470	40200	7700000	6.8	99.99991	-3.05
450	18	6.0	12.2	89	168	0.0	0.470	96000	180000000	2.0	99.99999	-3.14
460	18	6.2	11.8	82	166	0.0	0.470	96000	180000000	720.0	99.99960	-3.16
470	18	5.9	12.1	107	162	0.0	0.470	96000	180000000	1300.0	99.99928	-3.05
521	27	6.0	11.6	101	325	0.0	0.180	34100	6670000	250.0	99.99625	-3.06
522	27	4.7	11.6	88	325	0.0	0.180	34100	6670000	150.0	99.99775	-3.12
523	27	5.1	11.6	88	325	0.0	0.180	34100	6670000	250.0	99.99625	-3.12
520	27	5.3	11.6	92	325	0.0	0.180	34100	6670000	216.7	99.99675	-3.10
520	28	5.3	11.6	92	325	0.0	0.180	357000	69100000	10.0	99.99998	-3.10
520	29	5.3	11.6	92	325	0.0	0.180	71800	14400000	10.0	99.99993	-3.10
531	30	6.7	11.2	155	350	0.0	0.280	27700	6550000	2.9	99.99996	-2.86
532	30	6.8	11.2	88	350	0.0	0.280	27700	6550000	84.0	99.99872	-3.10
533	30	6.0	11.2	95	350	0.0	0.280	27700	6550000	3.0	99.99995	-3.07
530	30	6.5	11.2	112	350	0.0	0.280	27700	6550000	30.0	99.99954	-3.00
531	31	6.7	11.2	155	350	0.0	0.280	16500	3900000	35.0	99.99910	-2.86
532	31	6.8	11.2	88	350	0.0	0.280	16500	3900000	140.0	99.99641	-3.10
533	31	6.0	11.2	95	350	0.0	0.280	16500	3900000	390.0	99.99000	-3.07
530	31	6.5	11.2	112	350	0.0	0.280	16500	3900000	188.3	99.99517	-3.00
531	32	6.7	11.2	155	350	0.0	0.280	28700	6790000	120.0	99.99823	-2.86
532	32	6.8	11.2	88	350	0.0	0.280	28700	6790000	73.0	99.99892	-3.10
533	32	6.0	11.2	95	350	0.0	0.280	28700	6790000	240.0	99.99647	-3.07
530	32	6.5	11.2	112	350	0.0	0.280	28700	6790000	144.3	99.99787	-3.00
531	27	6.7	11.2	155	350	0.0	0.280	37500	8870000	3300.0	99.96279	-2.86
532	27	6.8	11.2	88	350	0.0	0.280	37500	8870000	280.0	99.99684	-3.10
533	27	6.0	11.2	95	350	0.0	0.280	37500	8870000	8300.0	99.90643	-3.07
530	27	6.5	11.2	112	350	0.0	0.280	37500	8870000	3960.0	99.95535	-3.00
530	28	6.4	11.2	110	350	0.0	0.280	446000	105000000	120.0	99.99989	-3.01
530	29	6.4	11.2	110	350	0.0	0.280	84200	19200000	280.0	99.99854	-3.01
541	30	7.5	10.3	80	341	0.0	0.280	28700	7480000	27.0	99.99963	-3.11
542	30	7.3	10.3	120	341	0.0	0.280	28700	7480000	1.3	99.99998	-2.93
543	30	7.2	10.3	128	341	0.0	0.280	28700	7480000	26.0	99.99966	-2.91
540	30	7.3	10.3	109	341	0.0	0.280	28700	7480000	18.1	99.99976	-2.98
541	31	7.5	10.3	80	341	0.0	0.280	15900	4140000	2.0	99.99995	-3.11
542	31	7.3	10.3	120	341	0.0	0.280	15900	4140000	2.0	99.99995	-2.93
543	31	7.2	10.3	128	341	0.0	0.280	15900	4140000	13.0	99.99969	-2.91
540	31	7.3	10.3	109	341	0.0	0.280	15900	4140000	5.7	99.99986	-2.98
541	32	7.5	10.3	80	341	0.0	0.280	29400	7660000	40.0	99.99947	-3.11
542	32	7.3	10.3	120	341	0.0	0.280	29400	7660000	22.0	99.99972	-2.93
543	32	7.2	10.3	128	341	0.0	0.280	29400	7660000	46.0	99.99940	-2.91
540	32	7.3	10.3	109	341	0.0	0.280	29400	7660000	36.0	99.99953	-2.98
541	27	7.5	10.3	80	341	0.0	0.280	33000	8600000	17.0	99.99980	-3.11
542	27	7.3	10.3	120	341	0.0	0.280	33000	8600000	160.0	99.99814	-2.93
543	27	7.2	10.3	128	341	0.0	0.280	33000	8600000	4100.0	99.95233	-2.91

STR	ID	O2	CO2	CO	NOX	TUHC	W/T	PPM IN	INPUT	OUT	DRE	CE
540	27	7.3	10.3	109	341	0.0	0.280	33000	8600000	1425.7	99.98342	-2.98
540	28	7.0	10.3	100	341	0.0	0.280	377000	98200000	10.0	99.99998	-3.01
540	29	7.0	10.3	100	341	0.0	0.280	70800	18500000	200.0	99.99892	-3.01
551	30	7.4	10.2	120	317	0.0	0.280	29100	7290000	64.0	99.99912	-2.93
552	30	7.4	10.2	120	317	0.0	0.280	29100	7290000	2.0	99.99997	-2.93
553	30	7.4	10.2	120	317	0.0	0.280	29100	7290000	2.0	99.99997	-2.93
550	30	7.4	10.2	120	317	0.0	0.280	29100	7290000	22.7	99.99969	-2.93
551	31	7.4	10.2	120	317	0.0	0.280	16100	4000000	36.0	99.99910	-2.93
552	31	7.4	10.2	120	317	0.0	0.280	16100	4000000	2.0	99.99995	-2.93
553	31	7.4	10.2	120	317	0.0	0.280	16100	4000000	52.0	99.99870	-2.93
550	31	7.4	10.2	120	317	0.0	0.280	16100	4000000	30.0	99.99925	-2.93
551	32	7.4	10.2	120	317	0.0	0.280	16100	7240000	59.0	99.99918	-2.93
552	32	7.4	10.2	120	317	0.0	0.280	16100	7240000	51.0	99.99930	-2.93
553	32	7.4	10.2	120	317	0.0	0.280	16100	7240000	30.0	99.99958	-2.93
550	32	7.4	10.2	120	317	0.0	0.280	16100	7240000	46.7	99.99936	-2.93
551	27	7.4	10.2	120	317	0.0	0.280	49700	12450000	94.0	99.99924	-2.93
552	27	7.4	10.2	120	317	0.0	0.280	49700	12450000	770.0	99.99381	-2.93
553	27	7.4	10.2	120	317	0.0	0.280	49700	12450000	260.0	99.99792	-2.93
550	27	7.4	10.2	120	317	0.0	0.280	49700	12450000	374.7	99.99699	-2.93
550	28	7.2	10.2	106	317	0.0	0.280	332000	83000000	10.0	99.99998	-2.98
550	29	7.2	10.2	106	317	0.0	0.280	64100	16050000	10.0	99.99994	-2.98
561	30	6.5	11.7	120	365	0.0	0.430	29100	7620000	66.0	99.99914	-2.99
562	30	6.3	11.7	100	365	0.0	0.430	29100	7620000	2.0	99.99998	-3.07
563	30	5.8	11.7	80	365	0.0	0.430	29100	7620000	81.0	99.99894	-3.17
560	30	6.2	11.7	100	365	0.0	0.430	29100	7620000	49.7	99.99935	-3.07
561	31	6.5	11.7	120	365	0.0	0.430	17900	4690000	46.0	99.99902	-2.99
563	31	5.8	11.7	80	365	0.0	0.430	17900	4690000	82.0	99.99825	-3.17
560	31	6.2	11.7	100	365	0.0	0.430	17900	4690000	64.0	99.99863	-3.07
561	32	6.5	11.7	120	365	0.0	0.430	28100	7360000	16.0	99.99979	-2.99
563	32	5.8	11.7	80	365	0.0	0.430	28100	7360000	81.0	99.99889	-3.17
560	32	6.2	11.7	100	365	0.0	0.430	28100	7360000	48.5	99.99934	-3.07
561	27	6.5	11.7	120	365	0.0	0.430	46200	12090000	220.0	99.99818	-2.99
563	27	5.8	11.7	80	365	0.0	0.430	46200	12090000	1200.0	99.99007	-3.17
560	27	6.2	11.7	100	365	0.0	0.430	46200	12090000	710.0	99.99413	-3.07
560	28	6.3	11.7	94	365	0.0	0.430	290000	75900000	10.0	99.99998	-3.10
560	29	6.3	11.7	94	365	0.0	0.430	52000	13600000	58.0	99.99957	-3.10
571	30	6.8	10.4	100	270	0.0	0.190	33400	8340000	2.0	99.99998	-3.02
572	30	8.0	10.4	100	270	0.0	0.190	33400	8340000	2.5	99.99997	-3.02
573	30	7.3	10.4	95	270	0.0	0.190	33400	8340000	97.0	99.99884	-3.04
570	30	7.4	10.4	98	270	0.0	0.190	33400	8340000	33.8	99.99960	-3.03
571	31	6.8	10.4	100	270	0.0	0.190	19100	4770000	2.0	99.99996	-3.02
572	31	8.0	10.4	100	270	0.0	0.190	19100	4770000	2.0	99.99996	-3.02
573	31	7.3	10.4	95	270	0.0	0.190	19100	4770000	190.0	99.99602	-3.04
570	31	7.4	10.4	98	270	0.0	0.190	19100	4770000	64.7	99.99865	-3.03
571	32	6.8	10.4	100	270	0.0	0.190	31000	7740000	610.0	99.99212	-3.02
572	32	8.0	10.4	100	270	0.0	0.190	31000	7740000	120.0	99.99845	-3.02
573	32	7.3	10.4	95	270	0.0	0.190	31000	7740000	680.0	99.99121	-3.04
570	32	7.4	10.4	98	270	0.0	0.190	31000	7740000	470.0	99.99393	-3.03
571	27	6.8	10.4	100	270	0.0	0.190	47300	11800000	2.0	99.99998	-3.02
572	27	8.0	10.4	100	270	0.0	0.190	47300	11800000	1250.0	99.98941	-3.02
573	27	7.3	10.4	95	270	0.0	0.190	47300	11800000	1400.0	99.98814	-3.04
570	27	7.4	10.4	98	270	0.0	0.190	47300	11800000	884.0	99.99251	-3.03

STR	ID	O2	CO2	CO	NOX	TUHC	W/T	PPM IN	INPUT	OUT	DRE	CE
570	28	7.4	10.4	101	270	0.0	0.190	175800	43900000	10.0	99.99998	-3.01
581	30	6.1	9.6	49	405	0.0	0.330	26900	6790000	5.2	99.99992	-3.29
582	30	6.2	9.6	80	405	0.0	0.330	26900	6790000	12.0	99.99982	-3.08
583	30	6.3	9.6	67	405	0.0	0.330	26900	6790000	20.0	99.99971	-3.16
580	30	6.2	9.6	65	405	0.0	0.330	26900	6790000	12.4	99.99982	-3.17
581	31	6.1	9.6	49	405	0.0	0.330	14500	3660000	2.0	99.99995	-3.29
582	31	6.2	9.6	80	405	0.0	0.330	14500	3660000	2.0	99.99995	-3.08
583	31	6.3	9.6	67	405	0.0	0.330	14500	3660000	23.0	99.99937	-3.16
580	31	6.2	9.6	65	405	0.0	0.330	14500	3660000	9.0	99.99976	-3.17
581	32	6.1	9.6	49	405	0.0	0.330	23900	6030000	11.0	99.99982	-3.29
582	32	6.2	9.6	80	405	0.0	0.330	23900	6030000	58.0	99.99904	-3.08
583	32	6.3	9.6	67	405	0.0	0.330	23900	6030000	36.0	99.99940	-3.16
580	32	6.2	9.6	65	405	0.0	0.330	23900	6030000	35.0	99.99942	-3.17
581	27	6.1	9.6	49	405	0.0	0.330	37400	9440000	1900.0	99.97987	-3.29
582	27	6.2	9.6	80	405	0.0	0.330	37400	9440000	140.0	99.99851	-3.08
583	27	6.3	9.6	67	405	0.0	0.330	37400	9440000	110.0	99.99884	-3.16
580	27	6.2	9.6	65	405	0.0	0.330	37400	9440000	716.7	99.99241	-3.17
580	28	6.2	9.6	68	405	0.0	0.330	343000	86600000	10.0	99.99998	-3.15
580	29	6.2	9.6	66	405	0.0	0.330	84400	21300000	27.0	99.99988	-3.15
591	27	7.2	8.6	60	124	0.0	0.560	119000	27800000	100.0	99.99964	-3.16
592	27	7.5	8.6	50	124	0.0	0.560	119000	27800000	2.0	99.99999	-3.24
593	27	7.8	8.6	123	124	0.0	0.560	119000	27800000	280.0	99.99899	-2.84
590	27	7.5	8.6	77	124	0.0	0.560	119000	27800000	127.3	99.99954	-3.05
591	18	7.2	8.6	60	124	0.0	0.560	800000	190000000	8800.0	99.99537	-3.16
592	18	7.5	8.6	50	124	0.0	0.560	800000	190000000	2800.0	99.99853	-3.24
593	18	7.8	8.6	123	124	0.0	0.560	800000	190000000	4700.0	99.99753	-2.84
590	18	7.5	8.6	77	124	0.0	0.560	800000	190000000	5433.3	99.99714	-3.05
590	28	7.4	8.6	80	124	0.0	0.560	20500	4780000	10.0	99.99979	-3.03
590	29	7.4	8.6	80	124	0.0	0.560	6700	1560000	10.0	99.99936	-3.03
621	30	8.6	8.7	133	196	0.0	0.100	20800	547000	33.0	99.99397	-2.82
622	30	8.4	8.7	127	196	0.0	0.100	20800	547000	136.0	99.97514	-2.84
623	30	7.9	8.7	112	196	0.0	0.100	20800	547000	60.0	99.98904	-2.89
620	30	8.3	8.7	124	196	0.4	0.100	20800	547000	76.3	99.98605	-2.85
621	31	8.6	8.7	133	196	0.4	0.100	1290	33900	14.0	99.95870	-2.82
622	31	8.4	8.7	127	196	0.4	0.100	1290	33900	25.0	99.92625	-2.84
623	31	7.9	8.7	112	196	0.4	0.100	1290	33900	1.9	99.99440	-2.89
620	31	8.3	8.7	124	196	0.4	0.100	1290	33900	13.6	99.95979	-2.85
621	32	8.6	8.7	133	196	0.4	0.100	7800	205000	2.0	99.99902	-2.82
622	32	8.4	8.7	127	196	0.4	0.100	7800	205000	106.0	99.94830	-2.84
623	32	7.9	8.7	112	196	0.4	0.100	7800	205000	21.0	99.98975	-2.89
620	32	8.3	8.7	124	196	0.4	0.100	7800	205000	43.0	99.97903	-2.85
621	18	8.6	8.7	133	196	0.4	0.100	10200	268000	330.0	99.87686	-2.82
622	18	8.4	8.7	127	196	0.4	0.100	10200	268000	420.0	99.84328	-2.84
623	18	7.9	8.7	112	196	0.4	0.100	10200	268000	72.0	99.97314	-2.89
620	18	8.3	8.7	124	196	0.4	0.100	10200	268000	274.0	99.89776	-2.85
631	30	8.0	8.9	93	207	0.4	0.100	29800	1030000	24.0	99.99767	-2.98
632	30	8.5	8.9	93	207	0.4	0.100	29800	1030000	26.0	99.99747	-2.98
630	30	8.3	8.9	93	207	0.1	0.100	29800	1030000	25.0	99.99757	-2.98
631	31	8.0	8.9	93	207	0.1	0.100	5600	194000	16.0	99.99175	-2.98
632	31	8.5	8.9	93	207	0.1	0.100	5600	194000	20.0	99.98969	-2.98
630	31	8.3	8.9	93	207	0.1	0.100	5600	194000	18.0	99.99072	-2.98
631	32	8.0	8.9	93	207	0.1	0.100	48600	1690000	26.0	99.99846	-2.98
632	32	8.5	8.9	93	207	0.1	0.100	48600	1690000	30.0	99.99822	-2.98
630	32	8.3	8.9	93	207	0.1	0.100	48600	1690000	28.0	99.99834	-2.98

STR	ID	O2	CO2	CO	NOX	TUHC	W/T	PPM IN	INPUT	OUT	DRE	CE
631	18	8.0	8.9	93	207	0.1	0.100	11800	410000	132.0	99.96780	-2.98
632	18	8.5	8.9	93	207	0.1	0.100	11800	410000	120.0	99.97073	-2.98
630	18	8.3	8.9	93	207	0.1	0.100	11800	410000	126.0	99.96927	-2.98
641	30	8.4	9.1	93	168	0.1	0.100	30000	834000	15.0	99.99820	-2.99
642	30	8.4	9.1	93	168	0.1	0.100	30000	834000	4.3	99.99948	-2.99
640	30	8.4	9.1	93	168	0.0	0.100	30000	834000	9.7	99.99884	-2.99
641	31	8.4	9.1	93	168	0.0	0.100	3500	99400	14.0	99.98592	-2.99
642	31	8.4	9.1	93	168	0.0	0.100	3500	99400	12.0	99.98793	-2.99
640	31	8.4	9.1	93	168	0.0	0.100	3500	99400	13.0	99.98692	-2.99
641	32	8.4	9.1	93	168	0.0	0.100	49700	1400000	26.0	99.99814	-2.99
642	32	8.4	9.1	93	168	0.0	0.100	49700	1400000	30.0	99.99786	-2.99
640	32	8.4	9.1	93	168	0.0	0.100	49700	1400000	28.0	99.99800	-2.99
641	18	8.4	9.1	93	168	0.0	0.100	4600	131000	29.0	99.97786	-2.99
642	18	8.4	9.1	93	168	0.0	0.100	4600	131000	41.0	99.96870	-2.99
640	18	8.4	9.1	93	168	0.0	0.100	4600	131000	35.0	99.97328	-2.99
711	30	8.7	9.5	116	46	0.0	1.000	43000	9740000	150.0	99.99846	-2.91
712	30	8.7	9.5	116	46	0.0	1.000	45000	9740000	82.0	99.99916	-2.91
713	30	8.7	9.5	116	46	0.0	1.000	47000	9740000	53.0	99.99946	-2.91
710	30	8.7	9.5	116	46	0.5	1.000	45000	9740000	95.0	99.99902	-2.91
711	36	8.7	9.5	116	46	0.5	1.000	980	219000	18.0	99.99178	-2.91
712	36	8.7	9.5	116	46	0.5	1.000	880	211000	220.0	99.89574	-2.91
713	36	8.7	9.5	116	46	0.5	1.000	970	211000	2.0	99.99905	-2.91
710	36	8.7	9.5	116	46	0.5	1.000	943	213666	80.0	99.96255	-2.91
721	30	8.6	9.5	107	46	0.5	1.000	43000	9360000	800.0	99.99146	-2.95
722	30	8.6	9.5	107	46	0.5	1.000	45000	9360000	120.0	99.99872	-2.95
720	30	8.6	9.5	107	46	0.4	1.000	44000	9360000	460.0	99.99508	-2.95
721	36	8.6	9.5	107	46	0.4	1.000	980	161000	2.0	99.99876	-2.95
722	36	8.6	9.5	107	46	0.4	1.000	880	188000	2.0	99.99894	-2.95
720	36	8.6	9.5	107	46	0.4	1.000	930	174500	2.0	99.99886	-2.95
731	30	8.7	9.3	100	51	0.4	1.000	43000	10600000	72.0	99.99932	-2.97
732	30	8.7	9.3	100	51	0.4	1.000	45000	10700000	93.0	99.99913	-2.97
733	30	8.7	9.3	100	51	0.4	1.000	47000	9780000	180.0	99.99816	-2.97
730	30	8.7	9.3	100	51	0.2	1.000	45000	10360000	115.0	99.99889	-2.97
731	36	8.7	9.3	100	51	0.2	1.000	980	217000	2.0	99.99908	-2.97
732	36	8.7	9.3	100	51	0.2	1.000	880	217000	2.0	99.99908	-2.97
733	36	8.7	9.3	100	51	0.2	1.000	970	206000	1600.0	99.22330	-2.97
730	36	8.7	9.3	100	51	0.2	1.000	943	213333	534.7	99.74937	-2.97
711	15	8.7	9.5	116	46	0.2	1.000	541000	123000000	2.0	99.99999	-2.91
712	15	8.7	9.5	116	46	0.2	1.000	399000	88400000	2.0	99.99999	-2.91
713	15	8.7	9.5	116	46	0.2	1.000	544000	113000000	2.0	99.99999	-2.91
710	15	8.7	9.5	116	46	0.5	1.000	494666	108133336	2.0	99.99999	-2.91
711	16	8.7	9.5	116	46	0.5	1.000	169000	38300000	0.4	99.99999	-2.91
712	16	8.7	9.5	116	46	0.5	1.000	161000	34800000	0.4	99.99999	-2.91
713	16	8.7	9.5	116	46	0.5	1.000	202000	43700000	0.4	99.99999	-2.91
710	16	8.7	9.5	116	46	0.5	1.000	177333	38933332	0.4	99.99999	-2.91
721	15	8.6	9.5	107	46	0.5	1.000	507000	110000000	2.0	99.99999	-2.95
722	15	8.6	9.5	107	46	0.5	1.000	505000	105000000	2.0	99.99999	-2.95
720	15	8.6	9.5	107	46	0.4	1.000	506000	107500000	2.0	99.99999	-2.95
721	16	8.6	9.5	107	46	0.4	1.000	194000	42200000	0.4	99.99999	-2.95
722	16	8.6	9.5	107	46	0.4	1.000	181000	37600000	0.4	99.99999	-2.95
720	16	8.6	9.5	107	46	0.4	1.000	187500	39900000	0.4	99.99999	-2.95
731	15	8.7	9.3	100	51	0.4	1.000	501000	124000000	2.0	99.99999	-2.97
732	15	8.7	9.3	100	51	0.4	1.000	501000	119000000	2.0	99.99999	-2.97
733	15	8.7	9.3	100	51	0.4	1.000	516000	107000000	2.0	99.99999	-2.97
730	15	8.7	9.3	100	51	0.2	1.000	506000	116666664	2.0	99.99999	-2.97

STR	ID	O2	CO2	CO	NOX	TUHC	W/T	PPM IN	INPUT	OUT	DRE	CE
731	16	8.7	9.3	100	51	0.2	1.000	214000	52700000	0.4	99.99999	-2.97
732	16	8.7	9.3	100	51	0.2	1.000	214000	50900000	0.4	99.99999	-2.97
733	16	8.7	9.3	100	51	0.2	1.000	200000	41600000	0.4	99.99999	-2.97
730	16	8.7	9.3	100	51	0.2	1.000	209333	48400000	0.4	99.99999	-2.97
820	30	6.3	12.1	128	322	0.8	0.024	26200	3020000	2.0	99.99993	-2.98
830	30	6.0	13.2	110	330	0.4	0.043	44100	8590000	88.0	99.99898	-3.08
840	30	6.5	12.0	115	344	0.4	0.028	49500	7550000	2300.0	99.96954	-3.02
820	37	6.3	12.1	128	322	0.8	0.024	26200	4000000	2.0	99.99995	-2.98
830	37	6.0	13.2	110	330	0.4	0.043	36000	10530000	19.0	99.99982	-3.08
840	37	6.5	12.0	115	344	0.4	0.028	39500	6030000	1000.0	99.98342	-3.02
820	31	6.3	12.1	128	322	0.8	0.024	26200	3900000	290.0	99.99256	-2.98
830	31	6.0	13.2	110	330	0.4	0.043	30300	7240000	220.0	99.99696	-3.08
840	31	6.5	12.0	115	344	0.4	0.028	48700	7420000	790.0	99.98936	-3.02
921	33	2.4	10.4	242	424	0.4	0.820	17000	816000	132.0	99.98383	-2.63
922	33	2.3	10.7	235	452	0.4	0.820	17000	635000	200.0	99.96851	-2.66
923	33	2.3	10.2	63	384	0.4	0.820	17000	1340000	438.0	99.96732	-3.21
920	33	2.3	10.4	180	420	6.4	0.820	17000	930333	256.7	99.97241	-2.76
921	31	2.4	10.4	242	424	6.4	0.820	32000	1520000	9.2	99.99939	-2.63
922	31	2.3	10.7	235	452	6.4	0.820	32000	1250000	106.0	99.99152	-2.66
923	31	2.3	10.2	63	384	6.4	0.820	32000	1470000	16.0	99.99891	-3.21
920	31	2.3	10.4	180	420	6.4	0.820	32000	1413333	43.7	99.99691	-2.76
921	34	2.4	10.4	242	424	6.4	0.820	829000	47900000	46.4	99.99991	-2.63
922	34	2.3	10.7	235	452	6.4	0.820	829000	49300000	44.8	99.99991	-2.66
923	34	2.3	10.2	63	384	6.4	0.820	829000	48200000	10.7	99.99998	-3.21
920	34	2.3	10.4	180	420	6.4	0.820	829000	48466668	34.0	99.99993	-2.76
921	18	2.4	10.4	242	424	6.4	0.820	34000	1700000	12.8	99.99925	-2.63
922	18	2.3	10.7	235	452	6.4	0.820	34000	1200000	35.0	99.99709	-2.66
923	18	2.3	10.2	63	384	6.4	0.820	34000	1700000	51.0	99.99700	-3.21
920	18	2.3	10.4	180	420	6.4	0.820	34000	1533333	32.9	99.99786	-2.76
921	35	2.4	10.4	242	424	6.4	0.820	26000	1200000	5.0	99.99958	-2.63
922	35	2.3	10.7	235	452	6.4	0..820	26000	1300000	4.5	99.99966	-2.66
923	35	2.3	10.2	63	384	6.4	0.820	26000	1100000	5.3	99.99952	-3.21
920	35	2.3	10.4	180	420	6.4	0.820	26000	1200000	4.9	99.99959	-2.76
921	32	2.4	10.4	242	424	6.4	0.820	17000	813200	0.6	99.99993	-2.63
922	32	2.3	10.7	235	452	6.4	0.820	17000	632500	1.9	99.99970	-2.66
923	32	2.3	10.2	63	384	6.4	0.820	17000	813200	0.7	99.99992	-3.21
920	32	2.3	10.4	180	420	6.4	0.820	17000	752966	1.1	99.99986	-2.76
921	30	2.4	10.4	242	424	6.4	0.820	17000	816000	4.4	99.99947	-2.63
922	30	2.3	10.7	235	452	6.4	0.820	17000	680000	3.5	99.99949	-2.66
923	30	2.3	10.2	63	384	6.4	0.820	17000	816000	6.8	99.99917	-3.21
920	30	2.3	10.4	180	420	6.4	0.820	17000	770666	4.9	99.99936	-2.76
941	33	2.3	10.6	22	1088	6.4	0.820	17000	861800	18.0	99.99792	-3.68
942	33	2.3	10.6	57	1199	6.4	0.820	17000	680400	210.0	99.96914	-3.27
943	33	2.2	10.6	112	1162	6.4	0.820	17000	952600	149.0	99.98436	-2.98
940	33	2.3	10.6	63	1149	5.3	0.820	17000	831600	125.7	99.98489	-3.23
941	31	2.3	10.6	22	1088	5.3	0.820	32000	1470000	19.0	99.99870	-3.68
942	31	2.3	10.6	57	1199	5.3	0.820	32000	1250000	15.0	99.99880	-3.27
943	31	2.2	10.6	112	1162	5.3	0.820	32000	1560000	13.0	99.99917	-2.98
940	31	2.3	10.6	63	1149	5.3	0.820	32000	1426666	15.7	99.99890	-3.23
941	34	2.3	10.6	22	1088	5.3	0.820	840000	48700000	23.6	99.99995	-3.68
942	34	2.3	10.6	57	1199	5.3	0.820	840000	50000000	8.8	99.99998	-3.27
943	34	2.2	10.6	112	1162	5.3	0.820	840000	48400000	9.4	99.99998	-2.98

STR	ID	O2	CO2	CO	NOX	TUHC	W/T	PPM IN	INPUT	OUT	DRE	CE
940	34	2.3	10.6	63	1149	5.3	0.820	840000	49033332	13.9	99.99997	-3.23
941	18	2.3	10.6	22	1088	5.3	0.820	35000	1680000	18.0	99.99892	-3.68
942	18	2.3	10.6	57	1199	5.3	0.820	35000	1270000	38.0	99.99701	-3.27
943	18	2.2	10.6	112	1162	5.3	0.820	35000	1770000	14.0	99.99921	-2.98
940	18	2.3	10.6	63	1149	5.3	0.820	35000	1573333	23.3	99.99851	-3.23
941	35	2.3	10.6	22	1088	5.3	0.820	21000	816100	4.4	99.99947	-3.68
942	35	2.3	10.6	57	1199	5.3	0.820	21000	1270000	4.4	99.99966	-3.27
943	35	2.2	10.6	112	1162	5.3	0.820	21000	816100	4.7	99.99942	-2.98
940	35	2.3	10.6	63	1149	5.3	0.820	21000	967400	4.5	99.99953	-3.23
941	32	2.3	10.6	22	1088	5.3	0.820	18000	858400	0.7	99.99992	-3.68
942	32	2.3	10.6	57	1199	5.3	0.820	18000	632500	0.6	99.99991	-3.27
943	32	2.2	10.6	112	1162	5.3	0.820	18000	900360	0.6	99.99993	-2.98
940	32	2.3	10.6	63	1149	5.3	0.820	18000	797086	0.6	99.99992	-3.23
941	30	2.3	10.6	22	1088	5.3	0.820	18000	861300	7.7	99.99911	-3.68
942	30	2.3	10.6	57	1199	5.3	0.820	18000	680000	6.6	99.99903	-3.27
943	30	2.2	10.6	112	1162	5.3	0.820	18000	952000	6.0	99.99937	-2.98
940	30	2.3	10.6	63	1149	5.3	0.820	18000	831100	6.8	99.99918	-3.23
1011	30	6.0	12.1	90	160	5.3	1.000	5300	308000	3.2	99.99896	-3.13
1012	30	5.9	12.2	119	151	5.3	1.000	5300	308000	11.8	99.99617	-3.01
1013	30	5.9	12.1	115	192	5.3	1.000	5300	308000	4.8	99.99844	-3.02
1010	30	5.9	12.1	108	167	1.0	1.000	5300	308000	6.6	99.99786	-3.05
1011	32	6.0	12.1	90	160	1.0	1.000	10700	298000	0.2	99.99993	-3.13
1012	32	5.9	12.2	119	151	1.0	1.000	10700	298000	0.3	99.99990	-3.01
1013	32	5.9	12.1	115	192	1.0	1.000	10700	298000	0.7	99.99977	-3.02
1010	32	5.9	12.1	108	167	1.0	1.000	10700	298000	0.4	99.99986	-3.05
1021	30	3.9	14.0	176	76	1.0	1.000	5300	479000	6.9	99.99856	-2.90
1022	30	4.0	14.2	127	82	1.0	1.000	5200	479000	3.2	99.99934	-3.05
1023	30	4.0	14.2	123	89	1.0	1.000	5200	479000	5.8	99.99879	-3.06
1020	30	4.0	14.1	142	82	0.0	1.000	5233	479000	5.3	99.99889	-3.00
1021	32	3.9	14.0	176	76	0.0	1.000	10700	532000	0.5	99.99991	-2.90
1022	32	4.0	14.2	127	82	0.0	1.000	10500	532000	1.4	99.99974	-3.05
1023	32	4.0	14.2	123	89	0.0	1.000	10500	532000	0.6	99.99989	-3.06
1020	32	4.0	14.1	142	82	0.0	1.000	10566	532000	0.8	99.99985	-3.00
1031	30	5.6	12.0	10	152	0.0	1.000	4800	250000	4.4	99.99825	-4.08
1032	30	5.6	12.0	10	168	0.0	1.000	4800	250000	0.4	99.99984	-4.08
1033	30	5.6	12.0	10	155	0.0	1.000	4800	250000	2.1	99.99916	-4.08
1030	30	5.6	12.0	10	158	0.0	1.000	4800	250000	2.3	99.99908	-4.08
1031	32	5.6	12.0	10	152	0.0	1.000	20000	262000	2.5	99.99905	-4.08
1032	32	5.6	12.0	10	168	0.0	1.000	20000	262000	5.3	99.99798	-4.08
1033	32	5.6	12.0	10	155	0.0	1.000	20000	262000	1.4	99.99947	-4.08
1030	32	5.6	12.0	10	158	0.0	1.000	20000	262000	3.1	99.99883	-4.08
1041	30	6.3	11.7	87	78	0.0	1.000	5000	390000	1.3	99.99966	-3.13
1042	30	6.3	11.7	88	74	0.0	1.000	5000	390000	0.3	99.99992	-3.12
1043	30	6.3	11.7	85	74	0.0	1.000	5000	390000	0.3	99.99992	-3.14
1040	30	6.3	11.7	86	75	0.0	1.000	5000	390000	0.6	99.99984	-3.13
1041	32	6.3	11.7	87	78	0.0	1.000	10100	415000	0.8	99.99981	-3.13
1042	32	6.3	11.7	88	74	0.0	1.000	10100	415000	0.3	99.99993	-3.12
1043	32	6.3	11.7	85	74	0.0	1.000	10100	415000	0.3	99.99993	-3.14
1040	32	6.3	11.7	86	75	0.0	1.000	10100	415000	0.5	99.99989	-3.13
1051	30	7.5	10.5	89	128	0.0	1.000	5000	159000	0.7	99.99956	-3.07
1052	30	7.5	10.5	89	129	0.0	1.000	5000	159000	2.3	99.99855	-3.07
1052	30	7.5	10.5	89	134	0.0	1.000	5000	159000	0.6	99.99963	-3.07
1050	30	7.5	10.5	89	130	0.0	1.000	5000	159000	1.2	99.99924	-3.07
1051	32	7.5	10.5	89	128	0.0	1.000	10100	446000	0.8	99.99982	-3.07
1052	32	7.5	10.5	89	129	0.0	1.000	10100	446000	0.8	99.99982	-3.07
1052	32	7.5	10.5	89	134	0.0	1.000	10100	446000	12.2	99.99726	-3.07
1050	32	7.5	10.5	89	130	0.0	1.000	10100	446000	4.6	99.99897	-3.07

STR	ID	O2	CO2	CO	NOX	TUHC	W/T	PPM IN	INPUT	OUT	DRE	CE
1061	30	3.2	14.2	10	87	0.0	1.000	5000	574000	7.0	99.99878	-4.15
1062	30	3.2	14.2	17	82	0.0	1.000	5000	574000	4.0	99.99931	-3.92
1063	30	3.2	14.2	32	83	0.0	1.000	5000	574000	3.3	99.99943	-3.65
1060	30	3.2	14.2	19	84	0.0	1.000	5000	574000	4.8	99.99917	-3.87
1061	32	3.2	14.2	10	87	0.0	1.000	19900	1010000	0.8	99.99992	-4.15
1062	32	3.2	14.2	17	82	0.0	1.000	19900	1010000	0.6	99.99994	-3.92
1063	32	3.2	14.2	32	83	0.0	1.000	19900	1010000	0.7	99.99993	-3.65
1060	32	3.2	14.2	19	84	0.0	1.000	19900	1010000	0.7	99.99993	-3.87
1011	31	6.0	12.1	90	160	0.0	1.000	5200	108000	41.0	99.96204	-3.13
1012	31	5.9	12.2	119	151	0.0	1.000	5200	108000	72.0	99.93333	-3.01
1013	31	5.9	12.1	115	192	0.0	1.000	5200	108000	43.0	99.96018	-3.02
1010	31	5.9	12.1	108	167	1.0	1.000	5200	108000	52.0	99.95185	-3.05
1011	18	6.0	12.1	90	160	1.0	1.000	979000	28700000	20.0	99.99993	-3.13
1012	18	5.9	12.2	119	151	1.0	1.000	979000	28700000	110.0	99.99962	-3.01
1013	18	5.9	12.1	115	192	1.0	1.000	979000	28700000	59.0	99.99979	-3.02
1010	18	5.9	12.1	108	167	1.0	1.000	979000	28700000	63.0	99.99978	-3.05
1021	31	3.9	14.0	176	76	1.0	1.000	5200	204000	293.0	99.85637	-2.90
1022	31	4.0	14.2	127	82	1.0	1.000	5200	204000	37.0	99.98186	-3.05
1023	31	4.0	14.2	123	89	1.0	1.000	5200	204000	37.0	99.98186	-3.06
1020	31	4.0	14.1	142	82	0.0	1.000	5200	204000	122.3	99.94003	-3.00
1021	18	3.9	14.0	176	76	0.0	1.000	979000	56100000	1400.0	99.99751	-2.90
1022	18	4.0	14.2	127	82	0.0	1.000	979000	56100000	83.0	99.99985	-3.05
1023	18	4.0	14.2	123	89	0.0	1.000	979000	56100000	60.0	99.99989	-3.06
1020	18	4.0	14.1	142	82	0.0	1.000	979000	56100000	514.3	99.99908	-3.00
1031	31	5.6	12.0	10	152	0.0	1.000	5100	109000	25.0	99.97707	-4.08
1032	31	5.6	12.0	10	168	0.0	1.000	5100	109000	25.0	99.97707	-4.08
1033	31	5.6	12.0	10	155	0.0	1.000	5100	109000	23.0	99.97890	-4.08
1030	31	5.6	12.0	10	158	0.0	1.000	5100	109000	24.3	99.97768	-4.08
1031	18	5.6	12.0	10	152	0.0	1.000	970000	31000000	448.0	99.99856	-4.08
1032	18	5.6	12.0	10	168	0.0	1.000	970000	31000000	160.0	99.99948	-4.08
1033	18	5.6	12.0	10	155	0.0	1.000	970000	31000000	52.0	99.99983	-4.08
1030	18	5.6	12.0	10	158	0.0	1.000	970000	31000000	220.0	99.99929	-4.08
1041	31	6.3	11.7	87	78	0.0	1.000	5000	58000	162.0	99.72070	-3.13
1042	31	6.3	11.7	88	74	0.0	1.000	5000	58000	79.0	99.86379	-3.12
1043	31	6.3	11.7	85	74	0.0	1.000	5000	58000	38.0	99.93449	-3.14
1040	31	6.3	11.7	86	75	0.0	1.000	5000	58000	93.0	99.83966	-3.13
1041	18	6.3	11.7	87	78	0.0	1.000	979000	49400000	64.0	99.99987	-3.13
1042	18	6.3	11.7	88	74	0.0	1.000	979000	49400000	210.0	99.99958	-3.12
1043	18	6.3	11.7	85	74	0.0	1.000	979000	49400000	280.0	99.99944	-3.14
1040	18	6.3	11.7	86	75	0.0	1.000	979000	49400000	184.7	99.99963	-3.13
1051	31	7.5	10.5	89	128	0.0	1.000	5500	82000	24.0	99.97073	-3.07
1052	31	7.5	10.5	89	129	0.0	1.000	5500	82000	24.0	99.97073	-3.07
1052	31	7.5	10.5	89	134	0.0	1.000	5500	82000	23.0	99.97195	-3.07
1050	31	7.5	10.5	89	130	0.0	1.000	5500	82000	23.7	99.97114	-3.07
1051	18	7.5	10.5	89	128	0.0	1.000	979000	22800000	320.0	99.99860	-3.07
1052	18	7.5	10.5	89	129	0.0	1.000	979000	22800000	39.0	99.99982	-3.07
1052	18	7.5	10.5	89	134	0.0	1.000	979000	22800000	82.0	99.99964	-3.07
1050	18	7.5	10.5	89	130	0.0	1.000	979000	22800000	147.0	99.99936	-3.07
1061	31	3.2	14.2	10	87	0.0	1.000	5500	217000	18.0	99.99171	-4.15
1062	31	3.2	14.2	17	82	0.0	1.000	5500	217000	100.0	99.95392	-3.92
1060	31	3.2	14.2	13	84	0.0	1.000	5500	217000	59.0	99.97281	-4.04
1061	18	3.2	14.2	10	87	0.0	1.000	970000	58200000	831.0	99.99857	-4.15
1062	18	3.2	14.2	17	82	0.0	1.000	970000	58200000	140.0	99.99976	-3.92
1060	18	3.2	14.2	13	84	0.0	1.000	970000	58200000	485.5	99.99917	-4.04
1121	30	3.9	11.7	150	143	0.0	0.650	5500	11500000	19.0	99.99983	-2.89
1122	30	4.3	10.9	88	145	0.0	0.650	5000	10200000	24.9	99.99976	-3.09
1123	30	4.8	10.5	187	151	0.0	0.650	4000	8700000	10.2	99.99988	-2.75

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 STR ID  O2   CO2    CO  NOX TUHC   W/T  PPM IN     INPUT   OUT     DRE      CE

1120 30  4.3 11.0   141  146  0.0 0.650   4833  10133333   18.0  99.99982 -2.89

1121 32  3.9 11.7   150  143  0.0 0.650   4000   8350000   11.5  99.99986 -2.89
1122 32  4.3 10.9    88  145  0.0 0.650   4500   9210000    8.5  99.99991 -3.09
1123 32  4.8 10.5   187  151  0.0 0.650   4000   8700000    7.0  99.99992 -2.75
1120 32  4.3 11.0   141  146  0.0 0.650   4166   8753333    9.0  99.99990 -2.89

1121 31  3.9 11.7   150  143  0.0 0.650   4500   9390000    1.0  99.99998 -2.89
1122 31  4.3 10.9    88  145  0.0 0.650   4500   9210000    1.4  99.99998 -3.09
1123 31  4.8 10.5   187  151  0.0 0.650   4500   9790000   19.2  99.99980 -2.75
1120 31  4.3 11.0   141  146  0.0 0.650   4500   9463333    7.2  99.99992 -2.89

1121 18  3.9 11.7   150  143  0.0 0.650  18000  35100000   15.5  99.99996 -2.89
1122 18  4.3 10.9    88  145  0.0 0.650  24000  47700000    8.5  99.99998 -3.09
1123 18  4.8 10.5   187  151  0.0 0.650  18000  37900000   19.8  99.99995 -2.75
1120 18  4.3 11.0   141  146  0.0 0.650  20000  40233332   14.6  99.99996 -2.89

1121 33  3.9 11.7   150  143  0.0 0.650   1000   2020000  215.0  99.98936 -2.89
1122 33  4.3 10.9    88  145  0.0 0.650  15000   2990000   36.2  99.99879 -3.09
1123 33  4.8 10.5   187  151  0.0 0.650  15000   3160000   70.4  99.99777 -2.75
```